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LETTER

Mail Stop Amendment
Commissioner for Patents
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Sir:

Enclosed herewith are copies of the following documents mentioned in applicants' Amendment B dated June 7, 2010:

Chapter 6 of "Handbook of Optical Engineering", edited by Brian J. Thompson and Daniel Malacara, CRC Press 2001, Print ISBN 978-0-8247-9960-1, eBook ISBN 978-0-203-90826-6, point 6.3.1; and

Technical Programme of the 2005 SPIE Europe International Symposium on Optical Systems Design, Paper 5962-42, Session 5, entitled "*Design of off-axis diffractive optical elements in the resonance domain of light diffraction*".

An early and favorable action on the merits is respectfully requested.

Respectfully submitted,

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By: ______________________
William E. McCracken
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June 17, 2010

6

Diffractive Optical Components

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6.1 INTRODUCTION

An optical system can be thought of as a device that transforms input wavefronts into output wavefronts. The class of transformations that link the output to the input wavefronts in refractive–reflective optical systems is quite limited. For example it is not possible to design a refractive–reflective optical system for which the resultant image is three dimensional when the input wavefront is a collimated beam. This particular input–output transformation can be realized by using a hologram.

Holograms can also be made to have predefined optical transfer functions, in which case they are referred to as holographic optical elements (HOEs). The optical transfer function of an HOE is based on diffraction expressed by the diffraction equation,

$$\lambda = d(\sin\theta_1 + \sin\theta_2), \tag{6.1}$$

where θ_1 and θ_2 are the angles of incidence and diffraction, respectively, and d is the period of the diffraction grating.

The wavelength dependence of this grating will depend on its structure, as shown in Fig. 6.1. Consequently, HOEs are useful and sometimes indispensable components of optical systems when the source is monochromatic or when a wavelength-dependent system is desired.

The fundamental difference between a general hologram and an HOE is that the first one forms an image of some extended object that is recorded in holographic material in the form of a holographic interference pattern combining an object beam and a reference beam (Jannson *et al.*, 1994). This image is reconstructed using a beam with similar properties to the reference beam. On the other hand, an HOE is

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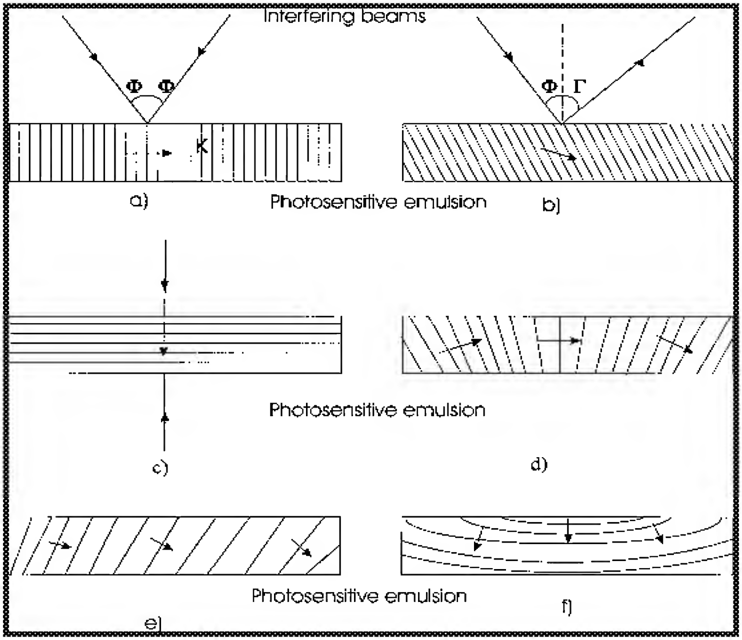

Figure 6.1 Some different fringes forms of the holographic optical elements (Jannson *et al.*, 1994).

recorded using a simple wavefront such as a spherical wave, a Gaussian, plane, elliptical, or any other elementary wave that satisfies, at least approximately, the eikonal equation (Sommerfeld, 1962).

In principle, given an arbitrary input wavefront, an HOE can be designed to transform into a desired output wavefront. In such a situation, the required HOE recording beams would most likely be produced by computer-generated holograms in conjunction with conventional refractive and reflective optical elements. Using the recent advances in micromachining and microelectronics techniques the fabrication of such structures with micron and submicron minimal details has become practical. Correspondingly, nonspectroscopic applications of gratings as diffractive optical elements (DOEs) have appeared. DOEs can not only replace reflective and refractive elements but in many cases can perform functions not even possible with conventional optics alone. The power of DOEs lies in their ability to synthesize arbitrary phase functions. They are used as components in novel devices, which were once considered too impractical but are now designed and fabricated. Complex microscopic patterns can be generated on the surface of many optical materials to improve the optical performance of existing designs as well as to make possible entirely new ones.

6.1.1 Holographic and Diffractive Optical Elements

In general, the term diffractive elements (DE) (or diffractive optical elements) refers to those that are based on the utilization of the wave nature of light. The HOEs and

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DOEs are based on grating composition (Jannson *et al.*, 1994). Both are lens-like; and its main difference is mostly in their fabrication. An HOE is produced by holographic recording, while a DOE is usually fabricated by a photolithographic method.

For both kinds of diffractive elements (HOEs and DOEs) the grating effect is dominant and defines their function and limitations. In general, grating dispersion is much stronger than prism dispersion. Thus, chromatic (wavelength) dispersion strongly influences (and limits) the imaging properties of HOEs and DOEs. Moreover, almost all applications of HOEs and DOEs are the result of effectively controlling chromatic dispersion and chromatic aberrations.

Although DOEs typically have a periodic (grating) structure that is always located at their surface as a surface relief pattern, HOEs also have a periodic structure that is located either on the surface or within the volume of the holographic material (Fig. 6.2).

This categorization can be divided into several subsections:

- diffractive lenses: elements that perform functions similar to conventional refractive lenses, e.g., they form images
- kinoforms: diffractive elements whose phase modulation is introduced by a surface relief structure
- binary optics: kinoforms produced by lithography
- diffractive phase elements (DPEs): diffractive elements that introduce phase change.

Regardless of the name or method of fabrication, diffractive optics can be understood with just a few basic tools. The properties of diffractive optics that are shared with conventional elements (focal length, chromatic dispersion, aberration

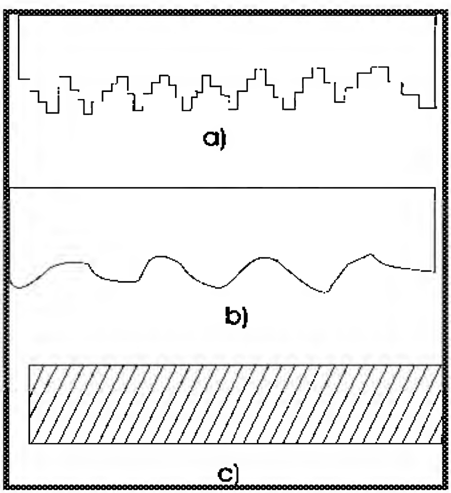

Figure 6.2 Illustration of diffractive optical elements (DOEs) and holographic optical elements (HOEs). (a) Multilevel DOE. (b) Surface (embossed) HOE. (c) Volume (Bragg) HOE; phase or amplitude modulation in the bulk of the material (Jannson *et al.*, 1994).

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contributions, etc.) do not depend on the specific type of diffractive element. Given a phase function or, equivalently, a grating spatial frequency distribution, the influence of the diffractive element or an incident ray for a specified diffraction order is found via the grating equation. The specific type involved (kinoform, binary lens, HOE, etc.) only influences the diffraction efficiency. Because of this reason, thoughout this chapter the general term of diffractive elements (DEs) will be used.

One factor that has stimulated much of the recent interest in diffractive optics has been the increased optical performance of such optical elements. This allows the fabrication of optical elements that are smaller, lighter, and cheaper to fabricate, are more rugged and have superior performance than the coventional optical components they often replace. In addition, the design capabilities for binary optics now available can make possible the design and manufacture of components having optical properties never before produced.

6.2 DESIGN ISSUES

Diffractive optical elements introduce a controlled phase delay into an optical wavefront by changing the optical path length, either by variating the surface height, or by modulating the refractive index as a function of position. Because of their unique characteristics, diffractive optical elements (DEs) present a new and very useful tool in optical design.

Innovative diffractive components have been applied in a number of new systems, such as laser-based systems, in which unusual features of these elements are utilized. Due to the great number of parameters that can be used to define a diffractive component, the efficient handling of this degree of freedom presents a technical challenge.

Probably the best way to describe the design procedure was presented by Joseph Mait (1995) who divided it into three basic stages: analysis, synthesis, and implementation.

(a) Analysis. There are two important points. First, it is necessary to understand the physics of the image formation required by the proposed diffractive element (DE) that will determine the method to be used (Fig. 6.3). Among the methods available are scalar or vector diffraction theory, geometrical, Fresnel and Fourier transform, convolution, correlation, and rigorous theory. The choice of method depends on the required diffraction properties of the DE and will affect the complexity of the design algorithm and the definition and value of the measured performance.

Secondly, it is important to take into account the fabrication model (i.e., the degree of linearity of the material and the possible errors in its fabrication) in which the data generated by computer will be recorded.

(b) Synthesis. Identifing the appropriate scheme that represents mathematically the underlying physical problem, the appropriate optimization techniques, design metrics (i.e., diffraction efficiency, quantization or reconstruction error, modulation transfer function, aberrations, undesired light, glare, etc.) and their degree of freedom.

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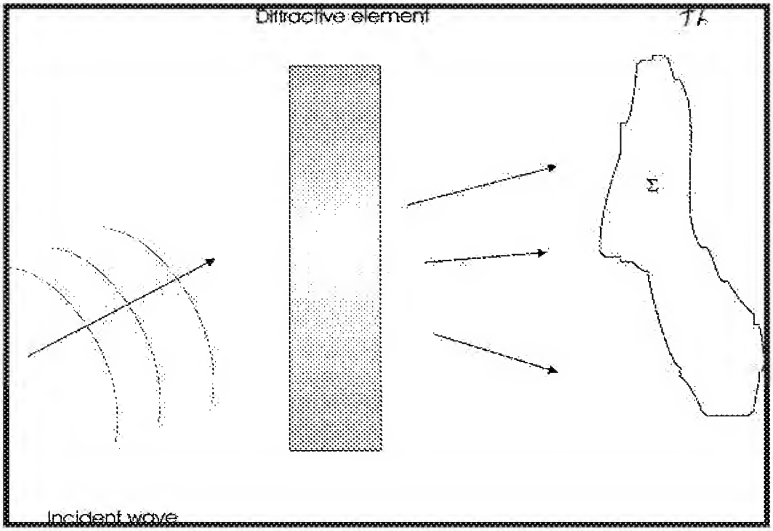

Figure 6.3 Basic geometry of diffractive optics (transmission mode). The incident wave is diffracted by the diffractive element (DE). The resultant amplitude distribution Σ must satisfy the requirements of the specific design.

Among the proposed procedures for optimization of the problem are the quantization, steepest descent, simulated annealing, and iterative Fourier algorithm, which in general can be classified as direct and indirect approaches.

In the direct method the performance of the primary metric is optimized. This method, although simple, can be time consuming. For indirect approaches, the optimization of an alternate metric for solving the design problem is necessary.

(c) Implementation. This step considers the execution of the design, and the fabrication and testing of the resulting diffracting element. It is an iterative procedure. The DE performance can be improved by using the data collected during the testing, or by introducing more data on the material response into the design.

6.2.1 Modeling Theories

The theoretical basis for modeling diffractive optics can be divided into three regimes: geometrical optics, scalar, and vector diffraction. The main features of each regime are described below.

6.2.1.1 Geometrical Optics

In this case, rays are used to describe the propagation of the diffracted wavefront but neglecting its amplitude variations; i.e., geometrical optics can predict the direction of diffraction orders but not their relative intensities. Despite these limitations, if a diffractive element is used in an application which is normally designed by tracing rays, then ray tracing coupled with simple efficiency estimates will usually be sufficient. The majority of these applications are conventional systems (imaging systems,

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collimating or focusing optics, laser relay systems, etc.). In such systems the diffractive element corrects residual aberrations (chromatic, monochromatic, or thermal) or replaces a conventional optic (e.g., a Fresnel lens replacing a refractive lens). In most of these cases, the diffractive optic is blazed for a single order and can be though as a generalized grating – one in which the period varies across the element.

Two methods are used: the grating equation and the Sweat model. In the grating equation (Welford, 1986), the diffraction of an incident wave is calculated on the grating point by point, and the propagation of the diffracted wave through the rest of the optical system. This diffracted beam is calculated with the grating equation, which is the diffractive counterpart to Snell's law or the reflection law. Deviation of the observed wavefront from a spherical shape constitutes the system's aberrations. This approach is very useful for the analysis of these aberrations. Usually a thin hologram has been assumed, with an amplitude transmission during reconstruction that is proportional to the intensity during the recording process. Other assumptions lead to additional diffraction orders and different amplitude distributions. For a given diffraction order, the imaging characteristics are the same, regardless of the diffracting structure assumed.

Sweat (1977; 1979) showed that a diffracting element is mathematically equivalent to a thin refracting lens in which the refractive index approaches infinity and the lens' curvatures converge to the substrate of the diffracting lens. Snell's law is then used to trace rays through this refractive equivalent of the diffractive element. As the index approaches infinity, the Sweat model approaches the grating equation. Almost all commercially available ray tracing software can handle either of these models.

6.2.1.2 Scalar Diffraction Theory

This approach must be used when the variations amplitude are not negligible, if the value of the system's diffraction efficiency cannot be separated from the rest of the design, or if the diffraction element cannot be approximated by a generalized grating. There are two fundamental assumptions usually involved in the application of scalar diffraction theory to the design and analysis of DEs. The first is that the optical field just past the DE can be described by a simple transmission function. In this case, the thin element approximation and, often, the paraxial approximation are used, together with the treatment of the electromagnetic wave as a scalar phenomenon. This ensures that the design problems are comparatively simple to solve. The second assumption is the choice of propagation method to transform this field to the plane of interest. On this point, it is possible to use the mathematical formulation of Fourier optics when the image is in the far field elements or Fresnel optics when it is in the near field.

Scalar diffraction theory is a simple tool for the analysis of diffractive optical elements. In this case, the diffractive optic is modeled as an infinitely thin phase plate and the light's propagation is calculated using the appropriate scalar diffraction theory.

Using the scalar approach, the design of optical diffracting elements for parallel optical processing systems has become possible. There are now highly efficient space invariant spot array generators that provide a signal in the Fourier transform plane of a lens, and space variant lens arrays which provide a signal in the device focal plane. Diffractive beam samplers and beam shapers are also in use. Some detailed designs can be found in the work of Mait (1995).

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Common optimization techniques include phase retrieval (Fienup, 1981), nonlinear optimization, and search methods or linear systems analysis.

6.2.1.2.1 The Resonant Domain

In recent years more attention has been paid to elements that push against the validity of the scalar approximations or violate them completely. These work in the so-called resonance domain, which is characterized by diffracting elements' structure, with size w, that lie within the illuminating wavelength (λ) range

$$\frac{\lambda}{10} < w < 10\lambda. \tag{6.2}$$

The strongest resonance effects are produced when the size of the elemental features approach the wavelength of the illuminating light. In this case, polarization effects and multiple scattering must be taken into account by using the electromagnetic theory rigorously. Such DE when working at optical wavelengths can be fabricated using techniques such as direct-write electron beam lithography.

In the resonant domain the diffraction efficiency changes significantly with a slight change of grating parameters such as period, depth, and refractive index.

This principle can be used to form different DEs such as a diffractive optic beam deflector for high-power laser systems, where laser-induced damage limits the usefulness of conventional elements. Reflection gratings operating as a polarization-sensitive beamsplitter has also been proposed (Lightbody *et al.*, 1995). Some numerical simulation uses a single diffraction grating in the resonant domain for pulse compression (Ichikawa, 1999).

6.2.1.3 Vector Diffraction Theory

The scalar theory fails when the output of the DE to be used is in its near field and when the minimum size of the elemental features is on the order of the illumination wavelength. Diffraction analysis of these situations requires a vector solution of Maxwell's equations that avoids the approximations present in scalar theories.

It has become possible to fabricate computer-synthesized diffractive elements where the size of the elemental features are as small as a fraction of a wavelength due to the progress in fabrication methods that are well known within integrated circuits technology (Wei *et al.*, 1994). This has been pushed toward compact small-size and low-cost elements by industral requirements. An additional requirement is to incorporate several sophisticated functions into a single component.

A relatively simple method for finding an exact solution of the Maxwell's equations for the electromagnetic diffraction is by grating structures. It has been used successfully and accurately to analyze holographic and surface-relief grating structures, transmission and reflection planar dielectric/absorption holographic gratings, dielectric/metallic surfaces relief gratings, multiplexed holographic gratings, etc. (Moharam *et al.*, 1994; Maystre, 1989).

In this theory, the surface-relief periodic grating is approximated by a stack of lamellar gratings. The electromagnetic fields of each layer of the stack are decomposed into spatial harmonics having the same periodicity as the grating. These spatial harmonics are determined by solving a set of coupled wave equations, one for each layer. The electromagnetic fields within each layer are matched to those in the two adjacent layers and to the fields associated with the backward and forward

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propagating waves or evanescent waves in two exterior regions. The amplitudes of the diffracted fields are obtained by solving this system of equations.

Rigorous methods have led to several approaches: the integral, differential, or variational (Noponen and Saarinen, 1996; Mirotznik *et al.*, 1996); analytic continuation (Bruno and Reitich, 1995); and variational methods and others (Prather, 1995). The integral approach covers a range of methods based on the solution of integral equations. The differential methods use a formally opposite approach of solving first- or second-order differential equations. In some methods the wave equations are solved by numerical integration through the grating. Recently a method has been proposed for the calculation or the diffraction efficiency that includes the response of photosensitive materials that have a nonuniform thickness variation or erosion of the emulsion surface due to the developing process (Kamiya, 1998).

Another method used to model all diffractive effects rigorously is to solve Maxwell's equations by using the finite element method (FEM) that is based on a variational formulation of the scalar wave equation. The FEM is a tool in areas such as geophysics, acoustics, aerodynamics, astrophysics, laser function, fluid dynamics and electromagnetics, as well as to model complex structures. With this method the analysis of complicated material structures can be calculated (Lichtenberg and Gallagher, 1994).

Some hybrid integral–variational methods have also been studied (Mirotznik *et al.*, 1996; Cotter *et al.*, 1995). In this case an FEM is used to solve the Helmholtz equation for the interior of a DE. A boundary element method, a Green's function approach, is used to determine the field exterior to the DE. These two methods are coupled at the surface of the DE by field continuity conditions. This work has been applied to the design of a subwavelength diffractive lens in which the phase is continuous and the analysis of diffraction from inhomogeneous scatterers in an unbounded region.

There is a similar method for the design of periodic subwavelength diffracting elements (Noponen *et al.*, 1995; Zhou and Drabik, 1995) that begins with an initial structure derived from scalar theory that uses simulated annealing to improve its performance. However, the infinitely periodic nature of the structures allows the rigorous coupled wave theory (RCW) developed by Moharam and Gaylord (1981) to be used for the diffraction model. These methods are flexible and have been applied to surface-relief gratings and to gradient-index structures.

6.2.1.3.1 Polarizing Components

Vector theory allows the analysis of the polarization properties of surface-relief gratings and diffracted beams whenever cross-coupling between the polarization states takes place. This is shown in the design and tolerance of components for magneto-optical heads (Haggans and Kostuk, 1991). Another example is polarizing beamsplitter (PBS) that combines the form birefringence of a spatial frequency grating, with the resonant refractivity of a multilayer structure (Tyan *et al.*, 1996). The results demonstrate very high extinction ratios (1,000,000:1) when PBS is operated at the designed wavelength and angle of incidence, and good average extinction ratios (from 800:1 to 50:1) when the PBS is operated for waves of 20° angular bandwidth, with wavelength ranging from 1300 nm to 1500 nm, combining features

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such as small size and negligible insertion losses. The design has been optimized using rigorous couple-wave analysis (RCWA).

6.2.1.4 Achromatic Diffractive Elements

Diffractive optical elements (DEs) operate at the wavelength for which they were designed. When operating at a different wavelength, chromatic aberrations arise. This is a characteristic feature of diffractive lenses. As described by Bennett (1976), a complete analysis of the chromatic aberrations of holograms must take into account the lateral displacement of an image point (lateral dispersion), and its longitudinal dispersion, the change of magnification, third- and higher-order chromatic aberrations, and amplitude variation across the reconstructed wavefronts from thick holograms.

The Abbe value of a diffractive lens v_{diff}, defined over the wavelength range from λ_{short} to λ_{long} (Buralli, 1994)

$$v_{\text{diff}} = \frac{\lambda_0}{(\lambda_{\text{short}} - \lambda_{\text{long}})} \tag{6.3}$$

will always be negative as $\lambda_{\text{long}} > \lambda_{\text{short}}$. The absolute value of v_{diff} is much smaller than the Abbe value for a conventional refractive lens. For this lens, aberration coefficients can be derived.

Since many potential DE applications require the simultaneous use of more than one wavelength, correction of chromatic aberration is essential.

The unique properties of the DE can be used to correct the aberration of the optical systems that consists of conventional optical elements and DEs by combining this with refractive elements to produce achromatic diffractive/refractive hybrid lenses for use in optical systems. Figure 6.4 shows some hybrid eyepiece designs. Many of these elements have been designed for use with spectral bands ranging from the visible to mid-wave infrared and long-wave infrared regions. These show that a DE is very effective in the correction of primary chromatic aberrations in the infrared region and of primary and secondary chromatic aberrations for visible optical systems. Generally, a DE can improve optical system performance while reducing cost and weight. One can reduce the number of lens elements by approximately one-third; additional benefits can include reducing the sensitivity of the system to rigid body misalignments.

The advantages offered by hybrid refractive–diffractive elements are particularly attractive in infrared systems where the material used is a significant proportion of the overall cost. Hybrid elements allow, for example, passive athermalization of a lens in a simple aluminum amount with a minimum number of elements in which two elements do the athermalization while the dispersive properties of a diffractive surface are used to achromatize the system. In order to realize their full effectivity, hybrid elements must include a conventional aspheric lens with a diffractive structure on one surface (McDowell *et al.*, 1994). Diamond turning permits the aspheric profile and diffractive features to be machined on the same surface in a single process.

Another method of achromatic DE design is that of Ford *et al.* (1996), where the DE acts differently for each of the two wavelengths. The phase-relief hologram can be transparent at one wavelength (λ) yet diffracting efficiently at another (λ') provided that the phase delay is an integral number of wavelengths at λ and a half-

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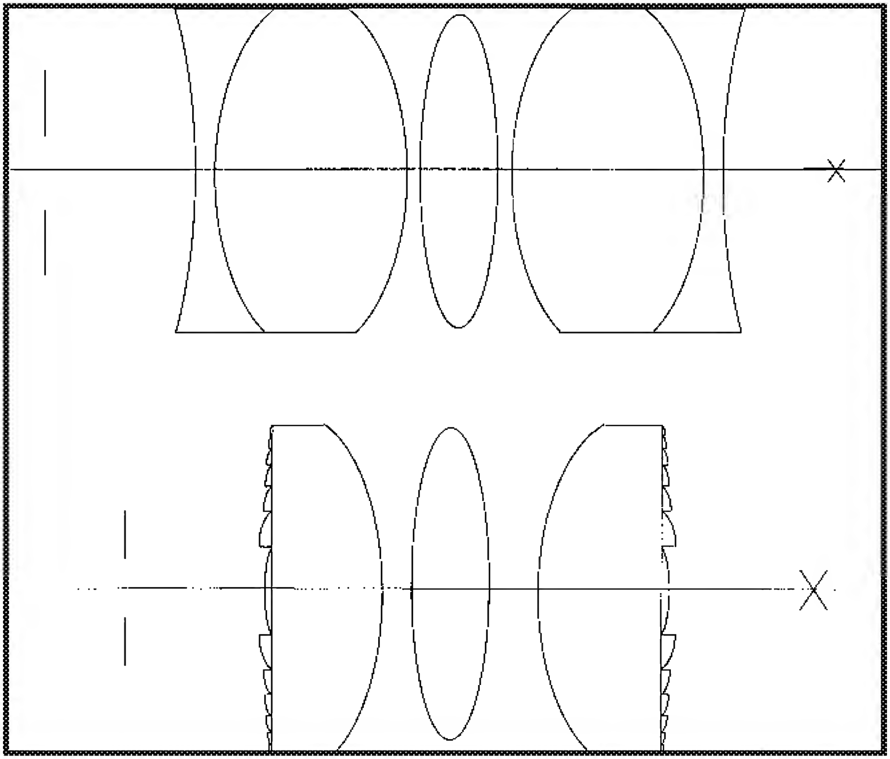

Figure 6.4 Eyepiece designs: (a) Erfle eyepiece and (b) an equivalent hybrid diffractive–refractive eyepiece (Missig and Morris, 1994).

integer number of wavelengths at λ'. In other words, there is an integral-multiple phase retardation of 2π to one wavelength until the suitable phase retardation of the secone wavelength is achieved (Fig. 6.5). In another method the DE is corrected for chromatic aberration designed by combinating two aligned DEs made of different materials (Arieli *et al.*, 1998).

6.3 FABRICATION TECHNIQUES

The design of a diffractive optical element must include specifications for microstructure necessary to obtain the desired performance. With an appropriate fabrication technique, these microstructures will introduce a change in amplitude or phase that alters the incident wavefront.

A factor that has stimulated much of the recent interest in diffractive optics has been new manufacturing techniques that give the designer greater control over the phase function that introduces the diffracting element, resulting in a reasonably high diffraction efficiency. In fact, a scalar diffraction theory analysis indicates that a properly designed surface profile can have a first-order diffraction efficiency of 100% at the design wavelength.

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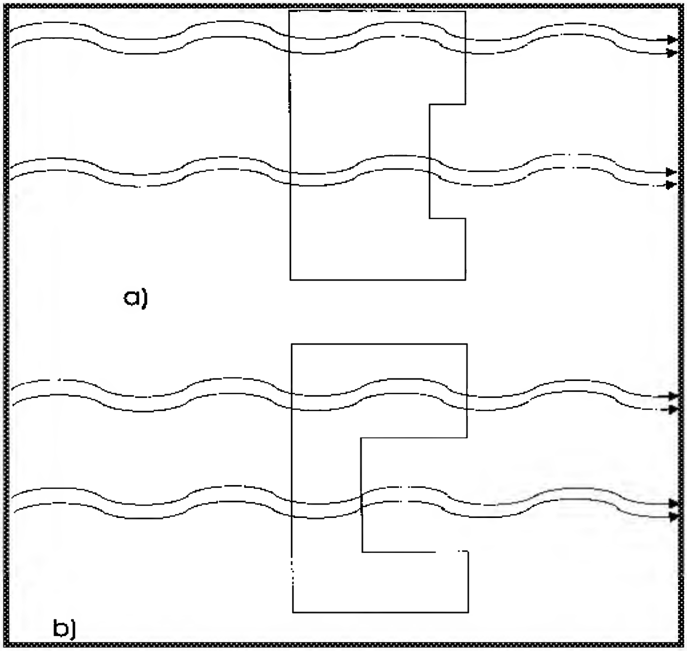

Figure 6.5 Effect of wavelength shift on (a) half-wave and (b) multiple-wave phase holograms. The path-length difference on wavelength shift is greater when the etch depth is optimum. With the correct etch depth, the phase delay at the second wavelength is zero, and there is no diffraction (Ford *et al.*, 1996).

In this section we discuss the main fabrication techniques. These are holographic recording, mask fabrication, and direct-writing techniques, as shown in Fig. 6.6.

6.3.1 Holographic Recording

Amplitude or phase modulation at high spatial frequencies can be obtained from a holographic recording. Off-axis diffractive optical elements have grating-like structures with submicron carrier frequency and diffraction efficiencies as high as 90%. The holographic recording process is rather complicated and is extremely sensitive to vibration, which can be avoided by using an active fringe stabilization system. With this technique, it is possible to obtain positioning errors below $\lambda/40$.

Probably one of the best-known materials is dichromated gelatine, which can be used to produce elements that introduce a phase-index modulation either in its bulk or on its surface. The advantages of this material are its high resolution, index modulation, diffraction efficiency, and low scattering. Further, factors such as humidity affect the holographic record in dichromated gelatine over time and hence the system is not stable unless it is properly sealed. This material is sensitive to the blue part of the spectrum, although there are some dyes that can be incorporated to make it sensitive to a different wavelength (Solano, 1987).

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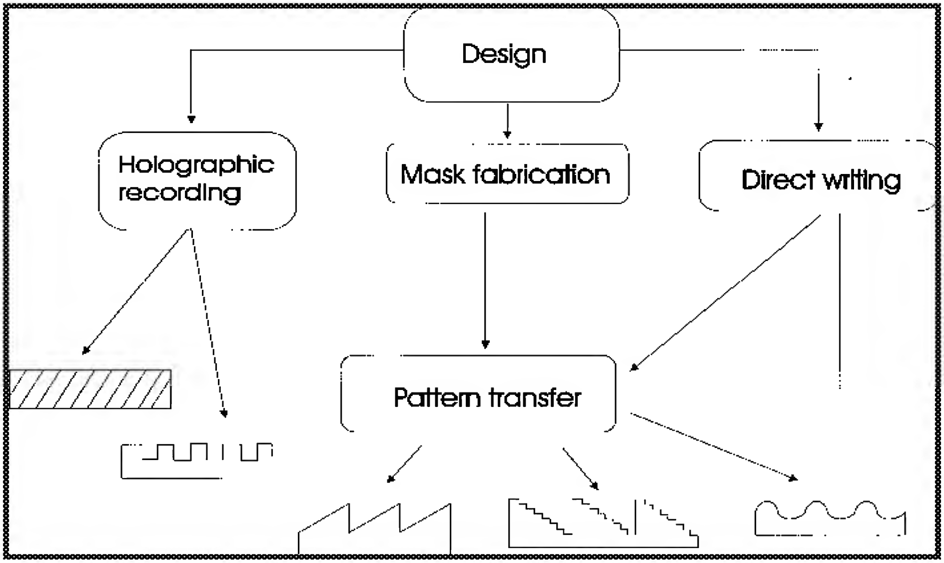

Figure 6.6 Main fabrication techniques of diffractive optical elements.

Other materials are photopolymers and are based on the photopolymerization of free-radical monomers such as acrylate esters (Lessard and Thompson, 1995). A relatively large number of free-radical monomers suitable for use in holographic recording have been developed. These allow the rapid polymerization of free-radical monomers with any of the common laser lines in the visible spectrum. Problems with these materials include the inhibition of free-radical polymerization due to the presence of dissolved oxygen. To compensate, a high initial exposure to oxygen is required, which causes a significant volume contraction, distorting the recorded fringe pattern. Reprocity failure, reduced diffraction efficiency at low spatial frequencies, and time-consuming post-exposure fixing are limitations that are overcome in a photopolymer based on cationic ring-opening polymerization (Close *et al.*, 1969). Among those photopolymers with good stability and high index modulation are those made by Dupont (Chen and Chen, 1998), the laboratory made with poly(vinylalcohol) as a base and the ones containing acrylamide, and some dyes (Pascual *et al.*, 1999).

Surface-relief DE can be fabricated by holographic exposure in different materials such as photoresists (Zaidi and Brueck, 1988), chalkogenide glasses (Tgran *et al.*, 1997), semiconductor-doped glasses (Amuk and Lawandy, 1997), and in liquid (Boiko *et al.*, 1991) and dry self-developing photopolymer materials (Calixto, 1987; Calixto and Paez, 1996; Neuman *et al.*, 1999), etc. Two types can be distinguished: those that approximate a staircase (Fresnel lens) and those based on diffractive optical elements (Fresnel zone plates, gratings, etc.).

It has been shown (Ehbets *et al.*, 1992) that almost any object intensity distribution can be interferometrically recorded and transferred to a binary surface relief using a strongly nonlinear development. As a result, the sinusoidal interference pattern is then transformed into a rectangular-shaped relief grating.

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6.3.2 Mask Fabrication: Binary Optical Elements

Binary optical elements are staircase approximations of kinoforms, which have multiple levels created by a photolithographic process, as shown in Fig. 6.7. The term binary optics comes from the binary mask lithography used to fabricate the multilevel structures.

The optical efficiency of a diffraction grating depends on the phase encoding technique. Binary optics is based in the creation of multilevel profiles, which requires exposure, development, and etching with different masks that are accurately aligned to each other. The number of phase levels realized through multiple binary masks depends on the specific encoding approach.

To explain the principle of these elements, assume that a blazed grating is to be written having the phase profile shown in Fig. 6.8(a), (Davis and Cottrell, 1994). Here the total phase shift over the grating is 2π radians and the period of the grating is defined as d. This grating would yield 100% diffraction efficiency into the first order. To fabricate this grating using binary optics techniques, masks are designed having increasingly finer resolutions of $d/2$, $d/4$, $d/8$, etc. Each mask is deposited sequentially onto a glass substrate. After the deposition of the first mask, the surface is etched in such a way that the phase difference between masked and unmasked areas is π radians, as shown in Fig. 6.8(b). However, the diffraction efficiency of this binary-phase-only mask is only 40.5%. To get higher diffraction efficiencies, increasingly finer masks are deposited one after the other and the substrate is etched in such a way as to produce increasingly smaller phase shifts. For the eight-phase level grating of Fig. 6.8(c), the diffraction efficiency reached 95%. However, to reach

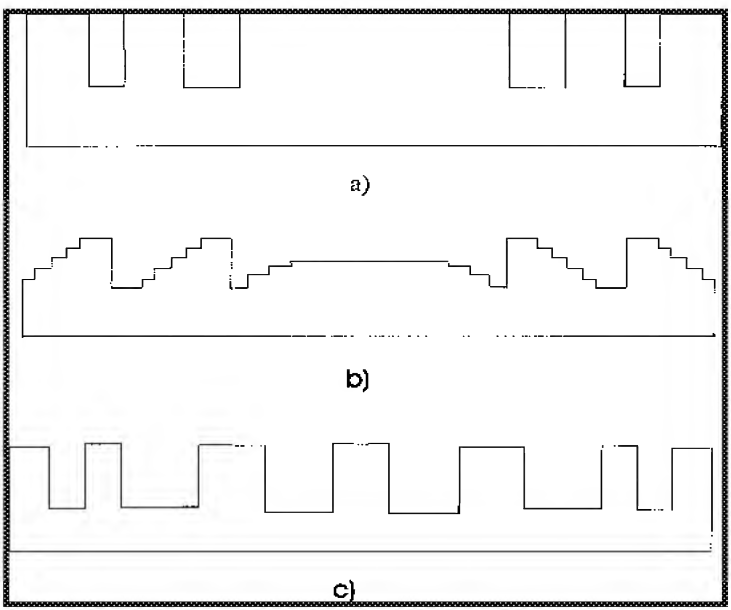

Figure 6.7 Binary optics fabricated by binary semiconductor mask lithography: (a) Fresnel zone, (b) Fresnel lenslet, and (c) Dammann grating.

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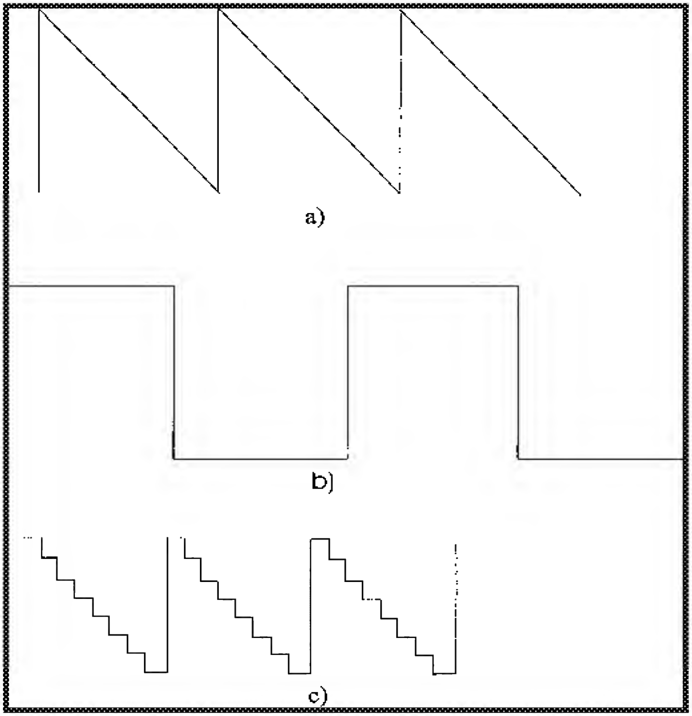

Figure 6.8 DE profiles: (a) phase profile for a grating with 100% diffraction efficiency; (b) binary phase grating profile; and (c) step phase grating profile (Davis and Cottrell, 1994).

higher diffraction efficiencies, the size of the elemental features must decrease in order to maintain the periodicity.

This staircase profile can be generated with masks or by using thin-film deposition (Beretta *et al.*, 1991).

These DE are constrained by spatial and phase quantization (Arrizon and Testorf, 1997). The complexity and quality of the reconstructed image determines the spatial complexity and phase resolution of the DE. The important issues in using masks are the alignment between the successive steps and the linewidth errors. This limits the fabrication of multilevel phase elements to three or four masks, corresponding to eight- or 16-phase levels.

Masks can be generated with electron-beam or laser beam lithography. These are amplitude elements that have to be transformed into surface-relief structures by exposure, chemical processing, and etching of the photoresist. These processes permit the fabrication of sawtooth, multilevel, or continuous profiles. For more rugged elements with high optical quality, the photoresist profiles are then transferred into a quartz substrate by standard techniques such as reactive ion etching.

With electron-beam lithography, one can write gratings with periods down to 100 nm, but beyond that they are limited by the proximity effect. Electron-beam lithography is a highly flexible means of generating arbitrary structures, even microlenses (Oppliger *et al.*, 1994). However, in the case of elementary feature sizes of the

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order of 50–100 nm, this approach is limited by the positioning accuracy during the writing process.

Binary and multilevel diffractive lenses with elementary feature sizes of the order of submicrometers have been produced on silicon and gallium phosphide wafers by using the CAD method, direct write electron-beam lithography, reactive ion etching, antireflection coating, and wafer dicing. Measurements indicate that it is possible to obtain aberration-free imaging and maximum diffraction efficiencies of 70% for lenses with numerical apertures (NAs) as high as 0.5. This technique has been applied to off-axis arrays for 18-channel parallel receiver modules (Haggans and Kostuk, 1991).

6.3.2.1 Photolithography

The interesting field of photolithography has developed as a result of the introduction of resist profiles to produce microoptical elements (Fresnel lenses, gratings, kinoforms, etc.). The thickness of the resist film that must be altered can be several micrometers thick to obtain the required profile depth of the optical element. The efficiency of those elements depend on the shape and quality of the resist profiles. Blazed and multilevel diffractive optical elements can reach a higher efficiency than binary optical elements.

Surface-relief lithography diffractive elements generated show promise for applications to magneto-optic heads for data storage due to their polarization selectivity, planar geometry, high diffractive efficiency, and manufacturability. Former applications of these elements had been limited due to the lack of information on their polarization properties.

The use of lithographic techniques opens the way to the development of optical elements that are economical, have high resolving power, and flexible design. These ideas are used in many systems at optical or near-infrared wavelengths.

6.3.2.2 Gray-Tone Masks

The gray-scale masks is an alternative approach to the multiple mask technique; it requires only one exposure and one etching process and yields a continuous profile. The gray levels are made by varying a number of transparent holes in a chromium mask that are so small that they are not resolved during the photolithographic step. Diffraction efficiencies reported are of the order of 75% for an element etched in fused silica, $\lambda = 633$ nm.

This process requires linearization of the photographic emulsion exposure as well as linearization of photoresist exposure: both are hard to reproduce (Däschner *et al.*, 1995).

6.3.3 Direct-Writing Techniques

High-intensity pulsed lasers can uniformly ablate material from the surface of a wide range of substrates (Braren *et al.*, 1993). Proper choice of laser wavelength allows a precise control of depth that can be applied in many materials that absorb in this region of the spectrum. These lasers have been used in lithographic processes. Direct-writing techniques yield higher phase resolutions (of the order of 64–128 phase levels) than photolithographic methods but at the expense of reduced spatial resolution.

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Another alternative, however, is to use an excimer laser with an ultraviolet waveguide to etch diffractive structures directly into the substrate without masks or intermediate processing steps (Fig. 6.9) (Duignan, 1994). This technique can be applied to a large spectrum of substrate materials, such as glass, diamond, semiconductors, and polymers, and can also reduce time and cost to produce a diffractive element.

Figures 6.10 and 6.11 show the fabrication steps and a schematic of one of the systems: in this particular case, a He–Cd laser is used to fabricate the DE on a photoresist substrate (Gale *et al.*, 1994).

Direct writing in photoresist, with accurate control of the process parameters, enables one to fabricate a complex continuous relief microstructure with a single exposure and development operation, which has been shown to produce excellent results (Ehbets *et al.*, 1992). Because writing times can be relatively long (many hours for typical microstructures of 1 cm^2) a latent image decay must be compensated. A number of factors determine the fidelity of the developed microstructure. The dominant experimental errors in the writing process are surface structures of the coated and developed photoresist films, the profile of the focused laser spot, the accuracy of the exposure dose, the line straightness, and the accuracy of the interline distance of the raster scan on the substrate.

An example of elements fabricated by direct laser writing in photoresist (Gale *et al.*, 1993) is a fanout element and diffractive microlens with NA = 0.5, which has been produced with a diffraction efficiency of 60%.

6.3.4 Replication Techniques

The main attraction of micro-optical elements lies in the possibility of mass production using replication technology.

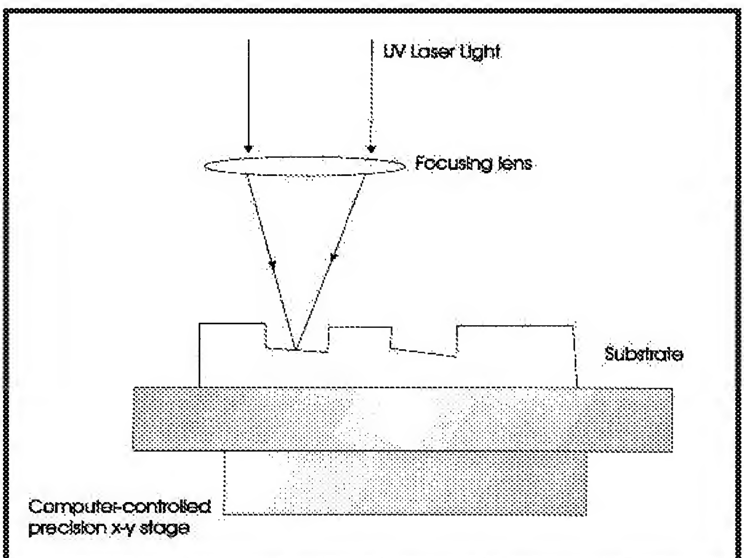

Figure 6.9 Direct-write photoablation of the substrate (Duignan, 1994).

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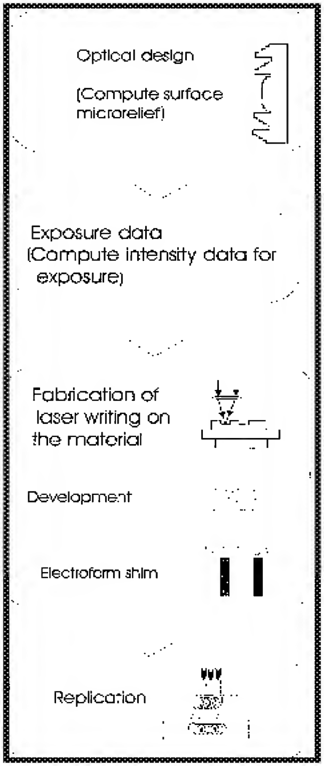

Figure 6.10 Fabrication steps for continuous-relief micro-optical elements (Gale *et al.*, 1994).

Replication technology is already well established for the production of diffractive foil, display holograms, and holographic security features in which the microrelief structures have a typical grating period of 0.5–1 μm with a maximum depth of about 1 μm. These are produced with a hot roller press applied to rolls of plastic up to 1 m wide and thousands of meters in length. (Kluepfel and Ross, 1991). For deeper microstructures, other replication techniques are required, such as hot-press, casting, or molding. In all cases it is necessary first to fabricate a metal shim, usually of nickel (Ni), by electroplating the surface of the microstructure. Figure 6.12 (Gale *et al.*, 1993) illustrates the steps involved in the fabrication of these shims. The recorded surface-relief microstructure in photoresist is first made conducting, either by the evaporation of a thin film of silver or gold of the order of 100 nm, or by using a commercial electronless Ni deposition bath. An Ni foil is then built up by electroplating this structure to a thickness of about 300 μm. Finally, the NI is separated from the resist/substrate and cleaned to give the master (first-generation) replication shim. This master shim can be used directly for replication, by hot-embossing or casting. It can also be supplied to a commercial shim facility for recombination to produce a large-area production shim.

The first-generation master can be used to generate multiple copies by electroplating further generations. The silver or nickel surface is first passivated by immer-

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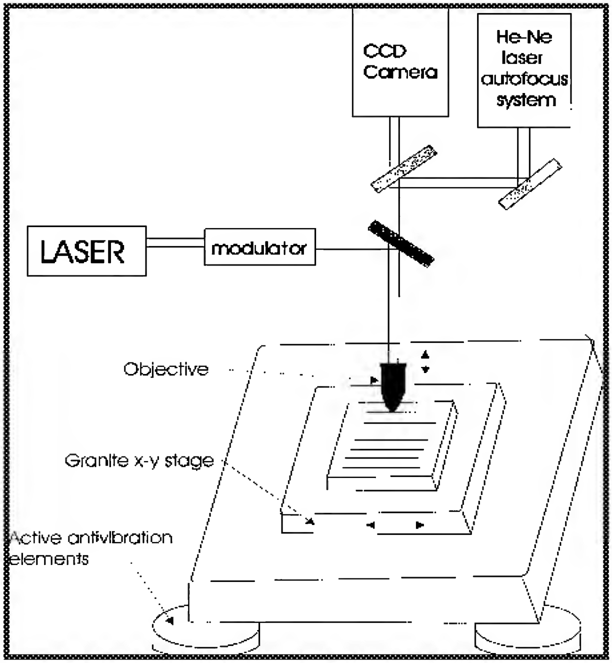

Figure 6.11 Schematic of laser-writing system for the fabrication of continuous relief micro-optical elements (Gale *et al.*, 1994).

sion in a dichromate solution or by O_2 plasma treatment, followed by further electroplating to form a copy that can readily be separated. In this way, numerous copies can be made from a single recorded microrelief.

Advances in the sol–gel process have made it possible to replicate fine-patterned surfaces in high-purity silica glass by a molding technique (Noguès and LaPaglia, 1989). The different types of diffractive optics that have already been replicated include binary grating, blazed grating, hybrid diffractive/refractive optical element, and plano kinoform. The requirements of the optics leads to an appropriate lens design, which then defines the design of the molds to be used to produce the optical components. To manufacture the mold, a tool that contains the required relief pattern must be fabricated. The mold is fabricated and used in the sol–gel process to produce prototype parts. Quality control then provides the necessary input to determine what, if any, changes are necessary in either mold or procedure for the final DE (Moreshead *et al.*, 1996).

There are three important advantages of the sol–gel replication process:

1. It provides a cost-effective way of producing optical elements with fine features. Although the mold surface is expensive, its cost can be amortized over a large volume of parts, thus making the unit cost relatively low.
2. The process can produce optical elements in silica glass, one of the best optical materials. The advantages of silica include a very high transmission over a broad wavelength range from 0.2 to 3.2 μm, excellent thermal sta-

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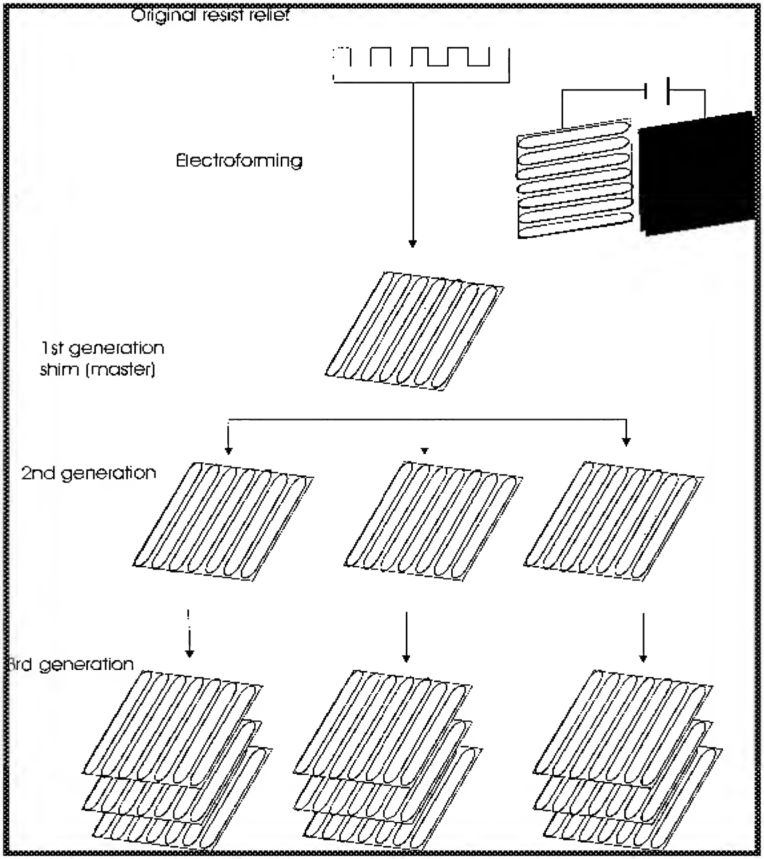

Figure 6.12 Fabrication of replication shims (Gale *et al.*, 1994).

bility, radiation hardness, and chemical treatment. Therefore, it can be used in harsh environments such as space, or for military uses and in high-power systems.

3. In the sol–gel replication process there is a substantial shrinkage that is controlled by adjusting the processing parameters. This shrinkage has been accurately quantified and has been found to be very uniform in all three dimensions, making it possible to fabricate parts with structures smaller than those made by other processing techniques. This reduces imperfections and tool marks by a factor of 2.5, reducing scattered light at the design wavelength.

Other techniques are compatible with the microfabrication techniques used in the semiconductor industry and require the generation of a gray-level mask such as that fabricated in high-energy beam sensitive (HEBS)-glass by means of a single electron-beam direct-write step (Wu, 1992). This mask was used in an optical contact aligner to print a multilevel DE in a single optical exposure. A chemically assisted

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ion-beam etching process has been used to transfer the DE structure from the resist into the substrate (Däschner *et al.*, 1995).

6.3.4.1 Plastic Optics

It is important to mention molded plastic DEs: they are low cost and can be mass-produced (Meyers, 1996). They can be produced in different shapes: rotationally symmetric, aspheric, and hybrid refractive/diffractive lenses. These are used in various applications, such as fixed focus and zoom camera lenses; camera viewfinders; diffractive achromatized laser-diode objectives; and asymmetric anamorphic diffractive concentrating and spectral filtering lenses for rangefinding and autofocus applications.

Planar micro-optical elements can be found in an increasing number of applications in optical systems and are expected to play a major role in the future. Typical elements for application at visible and infrared wavelengths are surface-relief microstructures with a maximum depth of about 5 μm. These can be mass-produced using current replication techniques such as hot-embossing, molding, and casting (Gale *et al.*, 1994).

6.4 DYNAMIC DIFFRACTIVE ELEMENTS

In recent years there has been a great deal of interest in active, dynamic diffractive elements that can be electrically programmed or switched. These elements can be divided into two classes. The first class uses an element-by-element addressing structure to produce diffracting patterns as spatial light modulators. The second class switches on a pre-patterned diffraction structure that has configured during fabrication. These devices could expand the range of application of the DE through the real-time control of an element's optical function. Both these devices have a large range of designs and methods for generating dynamically the phase or amplitude modulation of a spatial pattern in response to an electrical signal.

6.4.1 Programmable Diffraction Elements

Binary optics can be programmed to produce patterns with a large dynamic range. These have two functions. First, the spatial light modulator (SLM) serves as a programmable low-cost test for more complicated nonprogrammable binary optical elements. Secondly, the programmability of this system allows real-time image processing in which the optical element can be changed rapidly.

One way to obtain such elements is by using electro-optic material such as a liquid crystal (LC) layer. The LC materials exhibit a large field-induced birefringence effect, resulting in a local change in the index of refraction, polarization angle, or both. The main disadvantage is that the scale of the electrode patterns in these elements is larger than the microstructure needed for the diffractive elements. These elements show no diffraction effects except at their edges.

Therefore another allternative is to use the diffractive optical elements written onto an SLM (Parker, 1996). In this case, each phase region will be encoded onto an individual pixel element whose size is limited by the resolution of the SLM. These phase regions are limited by the operating physics of the SLM.

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One type of SLM system used is the magneto-optic spatial light modulator (MOSLM). This binary modulator consists of a two-dimensional array of magneto-optic modulators that are fabricated monolithically on a nonmagnetic substrate. Each element of the array can be electronically addressed through an array of crossed electrodes (Psaltis *et al.*, 1984). By contrast, the phase-only nematic liquid crystal monitor can encode continuous phase levels of up to 2π radians (Davis, 1994). Assuming that a wide range of phases can be encoded, the diffraction efficiency can be increased by using a number of pixels to encode each period of the grating. However, the maximum number of pixels is limited by the size and resolution of the SLM. For this reason an increase in the optical efficiency of the grating is offset by a decrease in its resolving power. Similar problems exist in encoding Fresnel lenses using SLMs.

The SLM has been used in Fresnel lenses, magneto-optic spatial light modulators, optical interconnections, lens arrays, subdiffraction limited focusing lenses, derivative lenses, nondiffractive lenses, and Damman gratings.

6.4.2 Switched Optical Elements

Switched optical elements use transmitting or reflecting structures that incorporate a material that exhibits an index of refraction that can be varied electrically. When an electric field is applied to the resulting composite structure, a range of predetermined optical characteristics emerge that spatially modulate or redirect light in a controlled matter. The effect on an incident wavefront may be controlled by varying the applied electric field.

These devices are capable of producing diffraction effects when a drive signal is applied, or in some designs, when it is removed.

Typically, SLMs are restricted to relatively small pixel arrays on the order of 256×256 and with correspondingly low diffraction efficiency. Monolithic holograms, on the other hand, have extremely high resolution, high optical quality, and diffraction efficiency, with 1 million times the pixel density. Such elements can be used in devices that are significantly different, especially from SLMs, if the material is also of sufficiently high optical quality to permit series stacking (Sutherland *et al.*, 1994). Figure 6.13 shows a generic device made of stacks of switchable holograms.

Among the different approaches to these switching DE is the placing of electrodes over a layer of liquid crystals to respond to the localized fields with two-dimensional distribution birefringence. It is possible also to fill a surface-relief binary optical element or a sinusoidal relief grating etched on dichromated gelatin with a layer of liquid crystals (Sainov *et al.*, 1987; Stalder and Ehbets, 1994). Reported switching times ranged between 20 and 50 ms for an applied voltage of $20\,V_{rms}$. Some other work involves special materials such as LC selective polymerization, or fabrication of holographic gratings by photopolymerization of liquid crystalline monomers that can be switched with the application of an electric field (Zhang and Sponnsler, 1992).

Most of the reported approaches involve liquid crystals in one way or another although, in principle, semiconductor techniques could also be used (Domash *et al.*, 1994).

One of the most popular materials is the polymer-dispersed liquid crystal (PDLC) formed *in situ* by a single-step photopolymer reaction (Sutherland *et al.*, 1994). These materials are composites of LC droplets imbedded in a transparent

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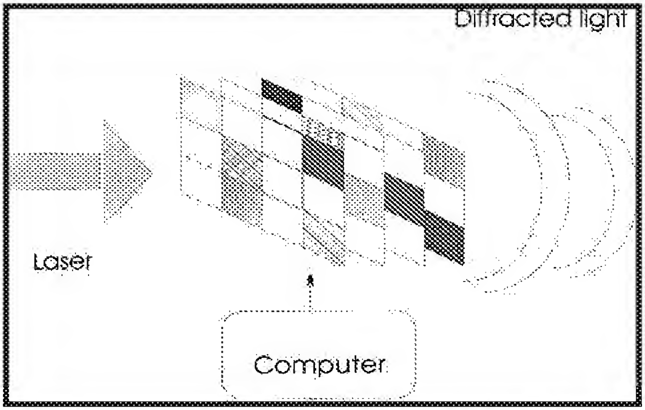

Figure 6.13 General active holographic interconnect device. Each plane contains an independent array of individually controlled patches of prerecorded holograms. By electrically addressing patches throughout the volume, many different diffractive functions can be programmed (Domash *et al.*, 1994).

polymer host whose refractive index falls between the LC ordinary and extraordinary indices. By modulating electrically the index match between LC droplets and polymer host, the characteristics of the volume holographic diffraction may be reduced. Fine-grained PDLCs have recently become available for electrically switchable holographic elements. The mechanism for the formation of the hologram grating is described by Sutherland, 1996. They have high diffraction efficiency, narrow angular selectivity, low voltage switching, and microsecond switching speed in elements with good optical quality as well as for the storage of the holographic image. Electro-optical read-out can be used with this new system material. Applications are for switchable notch filters for sensor application, reconfigurable optical interconnects in optical computing, fiber-optic switches, beam steering in laser radar, and tunable diffractive filters for color projection displays.

Dynamic-focus lenses that are controlled electrically are used in autofocusing devices for tracking in CD pickups, optical data storage components, and many other purposes. Some applications require continuous focusing; others call for switchable lenses with a discrete number of focal lengths. The basic concept is a diffractive lens material whose diffractive characteristics can be turned off by the application of an electric field. Using such a material, an electro-optic diffractive lens may be switched between two states – transparency (infinite focus) and finite focus.

A number of light-modulating SOE devices for display applications use structures that can be referred to as hybrid; i.e., structures that combine a fixed array of individually switched electrodes with a pre-patterned diffractive structure.

6.5 APPLICATIONS

6.5.1 Micro-optical Diffracting Elements

Micro-optical devices, such as diffractive and refractive microlenses have received considerable attention in the optics R&D community.

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Technological advances make it possible to micromachine optical and diffractive devices with structures that have the same order of magnitude as the wavelength of the incident light. Devices that were once considered impractical because of the limitations of bulk optics are now designed and easily fabricated with advanced microelectronics technology.

Micro-optical elements can be refractive, such as hemispherical lenslet and lenslet arrays, diffractive as kinoforms, grating structures, etc., or a combination of both such as Fresnel microlenses. They can be continuous surface-relief microstructures (Gale *et al.*, 1993), binary or multilevel reliefs or made by direct laser writing (Ehbets *et al.*, 1992).

The ability to combine various optical functions, e.g., focusing and deflection, and the reduced thickness and weight of DE in comparison to their refractive counterparts essentially explain the concern of diffractive optics in micro-optics.

In processing optical materials two main classes of diffractive optics are higher power lasers and their periphery (such as the interconnection of a high power Nd:YAG laser with a fiber bundle) and the use of DE to shape the laser in order to provide the illumination beam required for the same application such as the production of diffuse illumination with high-power CO_2 lasers (Wyroski *et al.*, 1994).

On the other hand, such elements can be applied to holography for memory imaging, nondestructive testing in interferometry, wavefront shaping, and as spatial filters. They have been many practical applications, such as diffraction gratings to shape the phase and polarization of incident fields, reflectors for microwave resonant heating systems, microwave lenses, mode converters in integrated optical devices, for dispersion compensation and pulse shaping in ultrafast optics, etc. (Lichtenberg and Gallagher, 1994).

Technology for making binary optics is a broadly based diffractive optics using advanced submicrometer processing tools and micromachining processes to create novel optical devices. One potential role of binary optics is to integrate very large scale integration (VLSI) of microelectronic devices with micro-optical elements (Montamedi, 1994). Because small feature sizes and stringent process control have been two major considerations, attention has focused on microlithography during the past few years. The rapid growth of commercial devices, such as miniature compact disk heads, demands both higher accuracy and lower-cost microlenses' fabrication methods.

Binary optics microlenses arrays are typically fabricated from bulk material by multi-mask-level photoresist patterning and sequential reactive-ion etching to form multistep phase profiles that approximate a kinoform surface. To fabricate an efficient microlens' array, eight-phase-level zones are necessary. The main parameters involved in its design are the wavelength (λ), the microlens' diameter (d'), the focal length (f), $f_{\#} = f/d'$, and the smallest feature size or critical dimension (D). For a typical binary optic microlens with eight phase levels the D value is $D = (\lambda f_{\#})/4$. The minimum value of VLSI is of the order of 0.5–1 μm. This limits the speed of binary optic microlenses designed for wavelengths (diode laser) from 0.632 μm to 0.850 μm to $f/6$ and $f/3$, respectively. Nevertheless, higher-speed microlenses can be fabricated for infrared applications.

As already mentioned, the diffraction efficiency of the light diffracted to the first-order focus increases with the number of phase levels. In practice, it decreases with the number of processing factors. Values of 90% have been obtained for eight-

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phase-level microlenses. The extent to which this is acceptable will depend on the application.

The surface relief of these diffractive microlenses has a planar structure of the order of the design wavelength. In a typical system this reduces the volume and weight of the optics relative to an all-refractive design.

Along with these developments in micro-optics technology is the development of micro-electro-mechanical (MEM) technology, which is based on micromachining methods for processing 3-D integrated circuits. MEM and micro-optics technologies have one critically important feature: both technologies are compatible with VSLI circuit processing. This feature means that the final device can be produced in volume at low cost. The standard VLSI process is generally confined to the surface of the wafer (Si or GaAs), extending only several micrometers under the surface. Multilayers of metal and dielectric are either deposited/grown on the surface or are etched into the surface.

Some micro-optical DE have been applied in optical choppers, optical switches, and scanners.

6.5.2 Optical Disk Memory Read–Write Heads

The optical head is an important component in optical disk storage. In it a laser beam is focused to a 1-μm diameter spot on the surface of the disk. The conventional optical head usually contains several optical elements such as a beamsplitter prism, a diffraction grating, a collimating lens, and a cylindrical lens, as shown in Fig. 6.14 (Huang *et al.*, 1994).

The disk moves under the optical axis of the head as it rotates. In this system it is necessary to detect and correct focus error to an accuracy of about ±1 μm. This focus error is determined from the total intensity of the light reflected by the optical disk.

Some systems have been suggested for replacing each of the optical elements with a diffractive micro-optical element performing the three optical functions required for an optical head: splitting the beam, focusing, and tracking the error signals (Fig. 6.15) (Huang *et al.*, 1994).

6.5.3 Optical Interconnects

Diffractive optics will play an important role in optical interconnects and optical interconnecting networks necessary in high-parallel-throughput processing. Diffractive optical interconnect elements provide several advantages over conventional bulk elements such as spherical and cylindrical lenses (Herzig and Dändliker, 1993).

One of the most simple devices for fanning out signals in optical interconnecting systems is the diffraction grating. A basic fan-out arrangement, consisting of a diffraction grating and a collecting lens, is shown in Fig. 6.16. Diffraction by a periodic pattern, such as in a Damman grating, divides the incident wave into many beams that are then focused by the collimating lens onto the detector plane. The amount of splitted light is determined by the specific pattern of the grating. The light focused in the different orders illuminates photodetectors or fibers, depending on the application of the system. These systems can compensate for wavelength dispersion and distortion that occur in diffractive fan-out elements (Schwab *et al.*, 1994).

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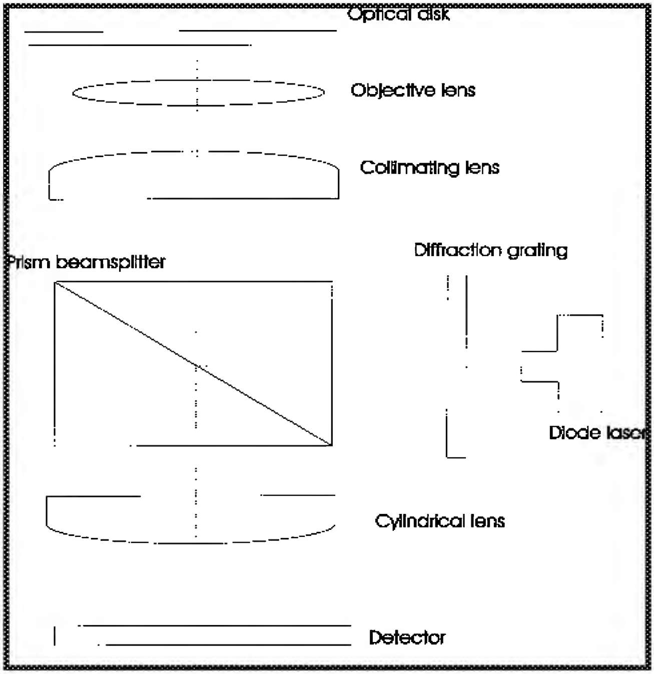

Figure 6.14 Configuration of a common optical head (Huang *et al.*, 1994).

The use of diffractive optics in interconnects is of considerable interest for several reasons. First, multiple diffractive optic elements can be cascaded on to planar substrates and more easily packaged with planar electronic substrates. To be effective, however, the diffractive optical system must separate and distribute optical signals in several dimensions. With diffractive optical interconnects for digital switching networks, current technology has the ability to form four-dimensional,

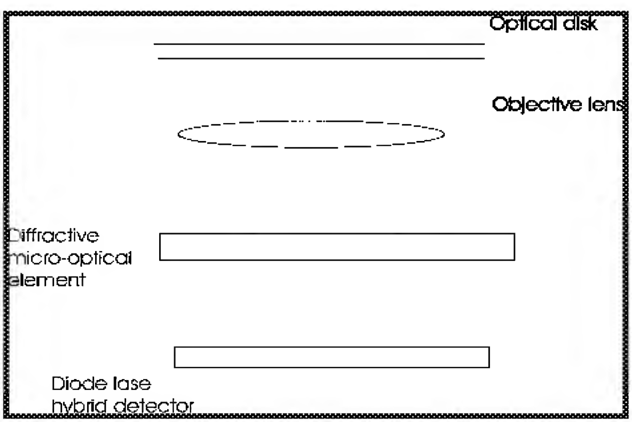

Figure 6.15 Optical head using a diffractive micro-optical element (Huang *et al.*, 1994).

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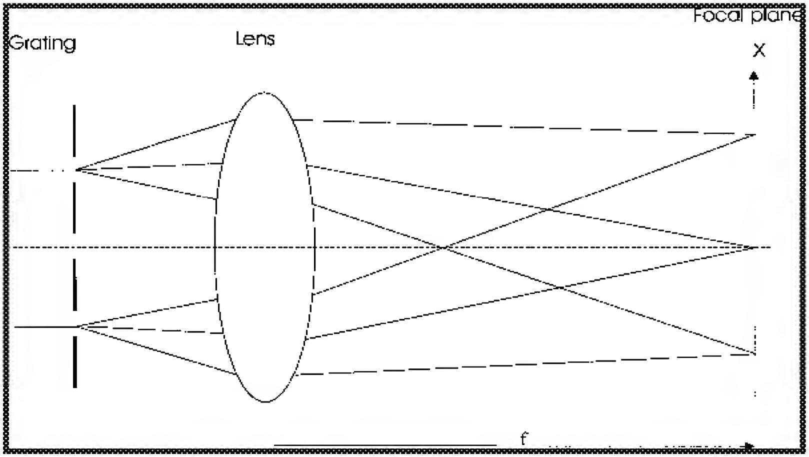

Figure 6.16 A grating is the simplest device for fanning out signals.

free-space optical interconnects with boundary conditions (Rakuljic *et al.*, 1992). The optics must be packaged with standard board substrates, and have alignment tolerances sufficient for board insertion, replacement, and changes of length caused by temperature variations.

Bidirectional information transfer is necessary at each information port. Parallel data transfer to increase information transfer rates is also important. It must be possible to broadcast greater data processing signal loads to multiple lateral and longitudinal locations.

In addition, the fabrication of microdiffractive optics using microlithographic and holography methods can produce many optical functions that can be used in both space variant and invariant systems. With these fabrication methods, units can be mass-produced, lowering overall system costs. Fabrication of diffractive optics uses computer-aided design (CAD) and microstructuring techniques. Reflection losses has been achieved using common techniques used in microelectronics technology such as ion-beam-sputter deposition. To reduce crosstalk and feedback, antireflection (AR) coatings or AR-structured surfaces have been suggested (Pawlowski and Kuhlow, 1994).

Diffractive optical elements (HOEs) have proven to be useful in optical interconnection and routing systems, especially where volume, weight, and design flexibility are important. Their characteristics can be increased by making them polarization-selective (Nieuborg *et al.*, 1997).

Finally, optical interconnect systems must be competitive in performance and cost with electrical interconnect methods. An example of a hybrid diffractive element design of a bidirectional interface is illustrated in Fig. 6.17 (Kostuk *et al.*, 1993).

6.5.4 Polarizing Elements

As mentioned earlier, another important application for diffractive elements is their ability to polarize light. Polarization-selective computer-generated holograms (CGH) or birefringent CGH (BCGH) have been found useful for image processing,

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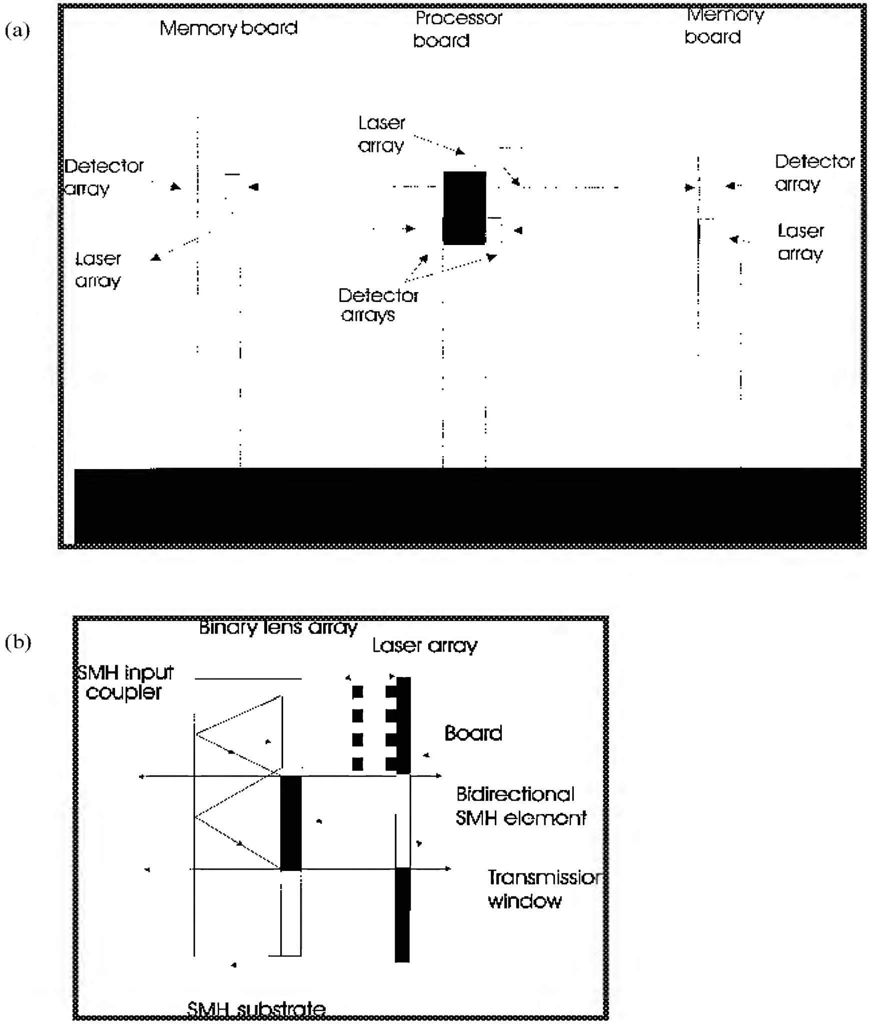

Figure 6.17 Schematic of (a) a single optical bus line connecting the processor board and (b) an expanded view showing the components on the central board transmitting to the adjacent boards through a bidirectional beamsplitter. This model uses a substrate-mode holographic (SMH) window element (Kostuk *et al.*, 1993).

photonic switching, and the packaging of optoelectronic devices and systems. With BCGH it is possible to perform two completely distinct functions using each of the two orthogonal polarizations.

Other applications are polarized beamsplitters (PBS) used for read–write magneto-optic disk heads (Ojima *et al.*, 1986), polarization-based imaging systems (Kinnstatter and Ojima, 1990; Kunstmann and Spitschan, 1990), and optical information processing such as free-space optical switching networks (McCormick *et al.*, 1992). These require the PBS to provide high extinction ratios, tolerate a wide

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angular bandwidth, a broad wavelength range of the incident light, and have a compact size for efficient packaging. For these applications tradtional birefringent structures such as the Wollaston prism or multilayer structures do not meet these requirements.

Diffractive optical elements (DE) have proven to be useful components in optical interconnection and routing systems, especially where volume, weight, and design flexibility are important. Their usefulness has been increased by making them polarization-selective using two wet etched anisotropic calcite substrates, joined at their etched surfaces and with their optical axes mutually perpendicular. The gap was filled with an index matching polymer (Nieuborg *et al.*, 1997). This element is less sensitive to fabrication errors. This method has been used to obtain elements that change the form of the emerging wavefront, depending on the polarization of the incident light, and has been applied in Fresnel lenses, gratings, and holograms that generate different images in their Fourier plane.

6.5.5 Holographic Memory Devices

An important characteristic of holographic memory is its ability to parallel input and record massive amounts of information into a memory. With this feature, memory devices can be created with high information quality. By information quality, we mean the product of the amount of recorded information and the retrieval rate.

The number of holograms that can be multiplexed in a given holographic system is primarily a function of the system's bandwidth in either temporal or spatial frequency, and the dynamic range of the material. One can record around 10 angle multiplexed holograms in a 38-μm thick film with diffraction efficiency of 10^{-3}. (Since it can typically work with holographic diffraction efficiencies on the order of 10^{-6}, we have sufficient dynamic range to record significantly more than 10 holograms.) The limitation in angular bandwidth can be alleviated with a thicker film, but scattering increases rapidly with thickness in these materials. Another method that has been previously used to increase the utilization of the available bandwidth of the system is fractal sampling grids (Mok, 1990), and peristrophic (consisting in turns) multiplexing has been used as a solution to the bandwidth limited capacity problem. With this method the hologram is physically rotated, with the axis of rotation perpendicular to the film's surface every time a new hologram is stored (Curtis and Psaltis, 1992).

6.5.6 Beam Shaping

In many applications one needs to reshape the laser beam intensity. The advantage of DE is that the beam energy is redistributed rather than blocked or removed, so that energy is preserved.

Some designs have been proposed using computer-generated holograms where the Gaussian beam has been converted into a ring distribution (Miler *et al.*, 1998), or using a two-element holographic system to obtain a flat distribution (Aleksoff *et al.*, 1991). Another proposed system is a Gaussian to top hat converter using a multilevel DE that can be fabricated with standard VLSI manufacturing equipment (Kosoburd *et al.*, 1994). This distribution is useful in material processing, laser radar, optical processing, etc. An interesting application is the collimation of high-power laser diodes (Goering *et al.*, 1999).

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Free-space digital optical systems require optical power supplies that generate two-dimensional arrays of uniform intensity (Gray *et al.*, 1993). The resultant spot arrays are used to illuminate optoelectronic logic devices' arrays to optically encode and transfer information. The favored method for creating these regularly spaced beam arrays is to illuminate a computer-designed Fourier-plane hologram using a collimated laser source. These surface-relief gratings, also referred to as multiple beamsplitters, are designed using scalar diffraction theory by means of a computer optimization process that creates an array of beams of uniform intensity (Gale *et al.*, 1993). The quality of the hologram is measured by its diffraction efficiency in coupling light into a set of designated orders and the relative deviation of the beam intensities from their targeted values.

Other beam shapers include the Laguerre–Gaussian beam, which has a phase singularity that propagates along its axis (Miyamoto *et al.*, 1999). Work has also been done to convert a Gaussian-profile beam into a uniform-profile beam in a one-dimensional optical system as well as rotationally symmetric optical systems both for different fractional orders and different parameters of the beam (Zhang *et al.*, 1998). Another important application is the pseudo-nondiffracting beam DE, characterized by an intensity distribution that is almost constant axially over a finite axial region and a long propagation distance along the optical axis (Liu *et al.*, 1998) and the axicons. An axicon is an optical element that produces a constant light distribution over a long distance along the optical axis. A diffractive axicon with a discrete phase profile can be fabricated using lithographic fabrication techniques. Other elements can be fabricated with linear phase profiles (Lunitz and Jahns, 1999).

Another beam-shaping procedure is the projection pattern that can be applied to change the physical or chemical state of a surface with visible light or ultraviolet radiation. Important applications in industrial production processes are microlithography and laser material processing.

In conventional methods of pattern projection a real value (mostly binary) transmission mask pattern is reproduced on the target surface by imaging or shadow casting. This pattern is then formed by diffraction of the illuminating wave at the mask where the diffracted wave is transformed by propagation, either through a lens or through free space, to the target surface.

The use of DE allows us to add phase components to the mask, giving a complex transmission coefficient. This method is called phase masking. It can be used to improve the steepness of edges in projected patterns by reduction of the spatial bandwidth. Also, the mask may be located at some distance from the target surface or of its optical conjugate. The mask then contains the pattern to be projected in a coded form. When it is in the far field of the target surface, this code is essentially a Fourier transformation (Velzel *et al.*, 1994).

REFERENCES

Aleksoff, C. C., K. K. Ellis, and B. G. Neagle, "Holographic Convertion of Gaussian Beam to Near-Field Uniform Beam," *Opt. Eng.*, **30**, 537–543 (1991).

Amuk, A. Y. and N. M. Lawandy, "Direct Laser Writing of Diffractive Optics in Glass," *Opt. Lett.*, **22**, 1030–1032 (1997).

Arieli, Y., S. Noach, S. Ozeri, and N. Eisenberg, "Design of Diffractive Optical Elements for Multiple Wavelengths," *Appl. Opt.*, **37**, 6174–6177 (1998).

Copyright © 2001 Marcel Dekker, Inc.

Arrizon, V. and M. Testorf, "Efficiency Limit of Spatially Quantized Fourier Array Illuminators," *Opt. Lett.*, **22**, 197–199 (1997).

Bennett, J., "Achromatic Combinations of Hologram Optical Elements," *Appl. Opt.*, **15**, 542–545 (1976).

Beretta, S., M. M. Cairoli, and M. Viardi, "Optimum Design of Phase Gratings for Diffractive Optical Elements Obtained by Thin-Film Deposition," *Proc. SPIE*, **1544**, 2–9 (1991).

Boiko, Y. B., V. M. Granchak, I. I. Dilung, V. S. Solojev, I. N. Sisakian, and V. A. Sojfer, "Relief Holograms Recording on Liquid Photopolymerizable Layers," in *Three-Dimensional Holography: Science, Culture, Education*, Jeong, T. H. and V. B. Markov (eds), *Proc. SPIE*, **1238**, 253–257 (1991).

Braren, B., J. J. Dubbowski, and D. P. Norton (eds), "Laser Ablation in Materials Processing: Fundamentals and Applications," *Material Research Society Proceedings*, **285**, 64–71 (1993).

Bruno, O. P. and F. Reitich, "Diffractive Optics in Nonlinear Media with Periodic Structure," *J. Opt. Soc. Am. A*, **12**, 3321–3325 (1995).

Buralli, D. A., "Using Diffractive Lenses in Optical Design," *OSA Technical Digest Diffractive Optics: Design, Fabrication, and Applications* **11**, 44–47 (1994).

Calixto, S., "Dry Polymer for Holographic Recording," *Appl. Opt.*, **26**, 3904–3910 (1987).

Calixto, S. and G. P. Paez, "Micromirrors and Microlenses Fabricated on Polymer Materials by Means of Infrared Radiation," *Appl. Opt.*, **35**, 6126–6130 (1996).

Chen, T. and Y. Chen, "Graded-Reflectivity Mirror Based on a Volume Phase Hologram in a Photopolymer Film," *Appl. Opt.*, **37**, 6603–6608 (1998).

Close, D. H., A. D. Jacobsob, J. D. Margerun, R. G. Brault, and F. J. McClung, *Appl. Phys. Lett.*, **14**, 159–160 (1969).

Cotter, N. P. K., T. W. Preist, and J. R. Sambles, "Scattering-Matrix Approach to Multilayer Diffraction," *J. Opt. Soc. Am. A*, **12**, 1097–1103 (1995).

Curtis, K. and D. Psaltis, "Recording of Multiple Holograms in Photopolymer Films," *Appl. Opt.*, **31**, 7425–7428 (1992).

Däschner, W., P. Long, M. Larson, and S. H. Lee, "Fabrication of Diffractive Optical Elements Using a Single Optical Exposure with a Gray Level Mask," *J. Vacuum Sci. & Techn. B*, **13**, 6–9 (1995).

Davis, J. A. and D. M. Cottrell, "Binary Optical Elements Using Spatial Light Modulators," *Proc. SPIE*, **2152**, 26, 226–236 (1994).

Domash, L. H., C. Gozewski, and A. Nelson, "Application of Switchable Polaroid Holograms," *Proc. SPIE*, **2152**, 13, 127–138 (1994).

Duignan, M. T., "Micromachining of Diffractive Optics with Excimer Lasers," *OSA Technical Digest Diffractive Optics: Design, Fabrication, and Applications*, **11**, 129–132 (1994).

Ehbets, P., H. P. Herzig, D. Prongué, and A. T. Gale, "High-Efficiency Continuous Surface-Relief Gratings for Two-Dimensional Array Generation," *Opt. Lett.*, **17**, 908–910 (1992).

Fienup, J. R., "Reconstruction and Synthesis Applications for an Iterative Algorithm," *Proc. SPIE*, **373**, 147–160 (1981).

Ford, J. E., F. Xu, and Y. Fainman, "Wavelength-Selective Planar Holograms," *Opt. Lett.*, **21**, 80–82 (1996).

Gale, M. T., M. Rossi, H. Schütz, P. Ehbets, H. P. Herzig, and D. Prongué, "Continuous-Relief Diffractive Optical Elements for Two-Dimensional Array Generation," *Appl. Opt.*, **32**, 2526–2533 (1993).

Gale, M. T., M. Rossi, J. Pedersen, and H. Schütz, "Fabrication of Continuous-Relief Micro-Optical elements by Direct Laser Writing in Photoresists," *Opt. Eng.*, **33**, 3556–3566 (1994).

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Gray, S., F. Clube, and D. Struchen, "The Holographic Mask Aligner," *Holographic Systems, Components and Applications, Neuchâtel, CH Conference Publication No. 379* (Institution of Electrical Engineers, London, 265 (1993)).

Goering, R., B. Hoefer, A. Kraeplin, P. Schreiber, E. Kley, and V. Schmeisser, "Integration of High Power Laser Diodes with Microoptical Components in a Compact Pumping Source for Visible Fiber Laser," *Proc. SPIE*, **3631**, 191–197 (1999).

Haggans, C. W. and R. Kostuk, "Use of Rigorous Coupled-Wave Theory for Designing and Tolerancing Surface-Relief Diffractive Components for Magneto-Optical Heads," *Proc. SPIE*, **1499**, 293–296 (1991).

Herzig, H. P. and R. Dändliker, "Diffractive Components: Holographic Optical Elements," in *Perspectives for Parallel Interconnects*, Lalanne Ph. and P. Chavel (eds), Springer-Verlag, Berlin, 1993.

Huang, G., M. Wu, G. Jin, and Y. Yan, "Micro-Optic Element for Optical Disk Memory Read-Write Heads," *Proc. SPIE*, **2152**, 30, 261–265 (1994).

Ichikawa, H., "Analysis of Femtosecond-Order Pulses Diffracted by Periodic Structures," *JOSA A*, **16**, 299–304 (1999).

Jannson, T., T. M. Aye, and G. Savant, "Dispersion and Aberration Techniques in Diffractive Optics and Holography," *Proc. SPIE*, **2152**, 5, 44–70 (1994).

Kamiya, N., "Rigorous Couple-Wave Analysis for Practical Planar Dielectric Gratings: 1. Thickness-Change Holograms and Some Characteristics of Diffraction Efficiency," *Appl. Opt.*, **37**, 5843–5853 (1998).

Kamiya, N., "Rigorous Couple-Wave Analysis for Practical Planar Dielectric Gratings: 2. Diffraction by a Surface-Eroded Hologram Layer," *Appl. Opt.*, **37**, 5854–5863 (1998).

Kinnstatter, K. and K. Ojima, "Amplitude Detection for the Focus Error in Optical Disks Using a Birefringent Lens," *Appl. Opt.*, **29**, 4408–4413 (1990).

Kluepfel, B. and F. Ross (eds), *Holography Market Place*, Ross Books, Berkeley, CA, 1991.

Kosoburd, T., M. Akivis, Y. Malkin, B. Kobrin, and S. Kedmi, "Beam Shaping with Multilevel Elements," *Proc. SPIE*, **2152**, 48, 214–224 (1994).

Kostuk, R. K., J. H. Yeh, and M. Fink, "Distributed Optical Data Bus for Board-Levels Interconnects," *Appl. Opt.*, **32**, 5010–5021 (1993).

Kunstmann, P. and H. J. Spitschan, "General Complex Amplitude Addition in a Polarization Interferometer in the Detection of Pattern Differences," *Opt. Commun.*, **4**, 166–172 (1971).

Lessard, R. A. and B. J. Thompson (eds), "Selected Papers on Photopolymers," *Proc. SPIE*, Milestone Series, **MS114** (1995).

Litchtenberg, B. and N. C. Gallagher, "Numerical Modeling of Diffractive Devices Using the Finite Element Method," *Opt. Eng.*, **33**, 3518–3526 (1994).

Lightbody, M. T. M., B. Layet, M. R. Taghizadeh, and T. Bett, "Design of Novel Resonance Domain Diffractive Optical Element," *Proc. SPIE*, **2404**, 96–107 (1995).

Liu, B., B. Domg, and B. Gu., "Implementation of Pseudo-Nondiffracting Beams by Use of Diffractive Phase Elements," *Appl. Opt.*, **37**, 8219–8223 (1998).

Lunitz, B. and J. Jahns, "Computer Generated Diffractive Axicons," *European Optical Society*, **22**, 26–27 (1999).

McCormick, F. B., F. A. P. Tooley, T. J. Cloonan *et al.*, "Experimental Investigation of a Free-Space Optical Switching Network by Using Symmetric Self-Electro-Optic-Effective Devices," *Appl. Opt.*, **31**, 5431–5446 (1992).

McDowell, A. J., P. B. Conway, A. C. Cox, R. Parker, C. W. Slinger, and A. P. Wood, "An Investigation of the Defects Introduced when Diamond Turning Hybrid Components for Use in Infrared Optical Ssytem," *OSA Technical Digest Diffractive Optics: Design, Fabrication, and Applications*, **11**, 99–102 (1994).

Mait, J. N., "Understanding Diffractive Optic Design in the Scalar Domain," *J. Opt. Soc. Am. A*, **12**, 2145–2150 (1995).

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Maystre D., "Rigorous Vector Theories of Diffraction Gratings," in *Progress in Optics*, Wolf, E. (ed.), North-Holland, Amsterdam, **XXI**, 1 (1984).
Meyers, M. M., "Diffractive Optics at Eastman Kodak Company," *Proc. SPIE*, **2689**, 31, 228–254 (1996).
Miler, M., I. Koudela, and I. Aubrecht, "Zone Areas of Diffractive Phase Elements Producing Focal Annuli," *Proc. SPIE*, **3320**, 210–213 (1998).
Mirotznik, M. S., D. W. Prather, and J. Mait, "Hybrid Finite Element-Bounder Element Method for Vector Modeling Diffractive Optical Elements," *Proc. SPIE*, **2689**, 2, 2–13 (1996).
Missig, M. D. and G. M. Morris, "Diffractive Optics Applied to Eyepiece Design," *OSA Technical Digest Diffractive Optics: Design, Fabrication, and Applications*, **11**, 57–60 (1994).
Miyamoto, Y., M. Masuda, A. Wada, and M. Takeda, "Electron-Beam Lithography Fabrication of Phase Holograms to Generate Laguerre–Gaussian Beams," *Proc. SPIE*, **3740**, 232 (1999).
Moharam, M. G. and T. K. Gaylord, "Rigorous Coupled-Wave Analysis of Surface-Gratings with Arbitrary Profiles," *J. Opt. Soc. Am.*, **71**, 1573–1574 (1981).
Moharam, M. G., D. A. Pommet, and E. B. Grann, "Implementation of the Rigorous Coupled-Wave Technique; Stability, Efficiency, and Covergence," *OSA Technical Digest Diffractive Optics: Design, Fabrication, and Applications*, **11**, 4–7 (1994).
Mok, F. H., "Angle-Multiplexed Storage of 5000 Holograms in Lithium Niobate," *Opt. Lett.*, **18**, 915–918 (1990).
Montamedi, M. E., "Micro-Opto-Electro-Mechanical Systems," *Opt. Eng.*, **33**, 3505–3517 (1994).
Montiel, F. and M. Neviere, "Differential Theory of Gratings: Extension to Deep Gratings of Arbitrary Profile and Permittivity through the R-Matrix Propagation Algorithm," *J. Opt. Soc. Am. A*, **11**, 3241 (1994).
Moreshead, W., J. L. Nogues, L. Howell, and B. F. Zhu, "Replication of Diffractive Optics in Silica Glass," *Proc. SPIE*, **2689**, 16, 142–152 (1996).
Neuman, J., K. S. Wieking, and K. Detlef, "Direct Laser Writing Surface Relief in Dry, Self-Developing Photopolymer Films," *Appl. Opt.*, **38**, 5418–5421 (1999).
Nieuborg, N., A. G. Kirk, B. Morlion, H. Thienpont, and L. P. Veretennicoff, "Highly Polarization-Selective Diffractive Optical Elements in Calcite with an Index-Matching Gap Material," *Proc. SPIE*, **3010**, 123–126 (1997).
Noguès, J. L. and A. J. LaPaglia, "Processing Properties and Applications of Sol–Gel Silica Optics," *Proc. SPIE*, **1168** (1989).
Noponen, E. and J. Saarinen, "Rigorous Synthesis of Diffractive Optical Elements," *Proc. SPIE*, **2689**, 6, 54–65 (1996).
Noponen, E., J. Turunen, and F. Wyrowski, "Synthesis of Paraxial Domain Diffractive Elements by Rigorous Electromagentic Theory," *J. Opt. Soc. Am. A*, **12**, 1128 (1995).
Ojima, M., A. Saito, T. Kaku *et al.*, "Compact Magnetooptical Disk for Coded Data Storage," *Appl. Opt.*, **25**, 483–489 (1986).
Oppliger, Y., P. Sixt, J. M. Stauffer, J. M. Mayor, P. Regnault, and G. Voirin, "One-step Shaping Using a Gray-Tone Cmask for Optical and Microelectronics Applications," *Microelectron. Eng.*, **23**, 449–452 (1994).
Parker, W. P., "Commercial Applications of Diffractive Switched Optical Elements (SOE's)," *Proc. SPIE*, **2689**, 27, 195–209 (1996).
Pascual, I., A. Marquez, A. Belendez, A. Fimia, J. Campos, and M. J. Yzuel, "Fabrication of Computer-Generated Phase Holograms Using Photopolymers as Holographic Recoding Material," *Proc. SPIE*, **3633**, 302–305 (1999).
Pawlowski, E. and B. Kuhlow, "Antireflection-Coated Diffractive Optical Elements Fabricated by Thin-Film Deposition," *Opt. Eng.*, **33**, 3537–3546 (1994).

Copyright © 2001 Marcel Dekker, Inc.

Prather, D. W., M. S. Mirotznik, and J. N. Mait, "Boundary Element Method for Vector Modelling Diffractive Optical Elements," *Proc. SPIE*, **2404**, 28–39 (1995).
Psaltis, D., E. G. Paek, and S. S. Venkatesh, "Optical Image Correlation with a Binary Spatial Light Modulator," *Opt. Eng.*, **23**, 698–704 (1984).
Rakuljic, G. A., V. Leyva, and A. Yariv, "Optical Data Storage by Using Orthogonal Wavelength-Multiplexed Volume Holograms," *Opt. Lett.*, **15**, 1471–1473 (1992).
Sainov, S., M. Mazakova, M. Pantcheva, and D. Tonchev, *Mol. Cryst. Liq. Cryst.*, **152**, 609–612 (1987).
Schwab, M., N. Lindlein, J. Schwider, Y. Amitai, A. A. Friesem, and S. Reinhorn, "Achromatic Diffractive Fan-out Systems," *Proc. SPIE*, **2152**, 12, 173–184 (1994).
Solano, C., P. C. Roberge, R. A. Lessard, Methylene Blue senstized Gelatinas a Photodensitive medium for Conventional and Polarizing Holography, "*Appl. Opt.*, **26**, 1989-1977 (1987).
Sommerfeld, A., *Optics*, Vol. IV, Academic Press, New York, 1962.
Stalder, M. and P. Ehbets, "Electrically Switchable Diffractive Optical Element for Image Processing," *Opt. Lett.*, **19**, 1–3 (1994).
Sutherland, R. L., L. V. Natarajan, V. P. Tondiglia, T. J. Bunning, and W. W. Adams, "Development of photopolymer-liquid crystal composite materials for dynamic hologram applications, Proc. SPIE, **2152**, 303–312, 1994b.
Sutherland, R. L., L. V. Natarajan, V. P. Tondiglia, T. J. Bunning, and W. W. Adams, "Electrically Switchable Volume Gratings in Polymer-Dispersed Liquid Crystal," *Appl. Phys. Lett.*, **64**, 1074–1076 (1994).
Sweat, W. C., "Describing Holographic Optical Elements as Lenses," *J. Opt. Soc. Am.*, **67**, 803–808 (1977).
Sweat, W. C., "Mathematical Equivalence between a Holographic Optical Element and a Ultra-High Index Lens," *JOSA*, **69**, 486–487 (1979).
Tgran, V. G., J. F. Viens, A. Villeneuve, K. Richardson, and M. A. Duguay, "Photoinduced Self-Developing Relief Gratings in Thin Film Chalcogenide As_2s Si_3 Glasses," *J. Lightwave Technol.*, **15**, 1343–1345 (1997).
Tyan, R. C., P. C. Sun, and Y. Fainman, "Polarizing Beam Splitters Constructed of Form-Birefringent Multilayer Grating," *Proc. SPIE*, **2689**, 8, 82–89 (1996).
Velzel, C. H. F., F. Wyrowski, and H. Esdink, "Pattern Projection by Diffractive and Conventional Optics: a Comparison," *Proc. SPIE*, **2152**, 24, 206–211 (1994).
Wei, M., E. H. Anderson, and D. T. Attwood, "Fabrication of Ultrahigh Resolution Gratings for X-ray Spectroscopy," *OSA Technical Digest Diffractive Optics: Design, Fabrication, and Applications*, **11**, 91–94 (1994).
Welford, W. T., *Aberrations of Optical System*, Adam Hilger Ltd., Boston, 1996.
Wu, C., "Method of Making High Energy Beam Sensitive Glasses," U.S. Patent No. 5,078,771 (1992).
Wyroski, F., H. Esdonk, R. Zuidema, S. Wadmann, and G. Notenboom, "Use of Diffractive Optics in Material Processing," *Proc. SPIE*, **2152**, 16, 139–144 (1994).
Zaidi, S. H. and S. R. J. Brueck, "High Aspect-Ratio Holographic Photoresist Gratings," *Appl. Opt.*, **27**, 2999–3002 (1988).
Zhang, J. and M. B. Sponsler, "Switchable Liquid Crystalline Photopolymer Media for Holography," *J. Am. Chem. Soc.*, **14**, 1516–1520 (1992).
Zhang, Y., B. Gu, B. Dong, and G. Yang, "Design of Diffractive Phase Elements for Beam Shaping in the Fractional Fourier Transform Domain," *Proc. SPIE*, **3291**, 58–67 (1998).
Zhou, Z. and T. J. Drabik, "Optimized Binary, Phase-Only Diffractive Optical Elements with Sub-wavelength Features for 1.55 μm," *J. Opt. Soc. Am. A*, **12**, 1104–1112 (1995).

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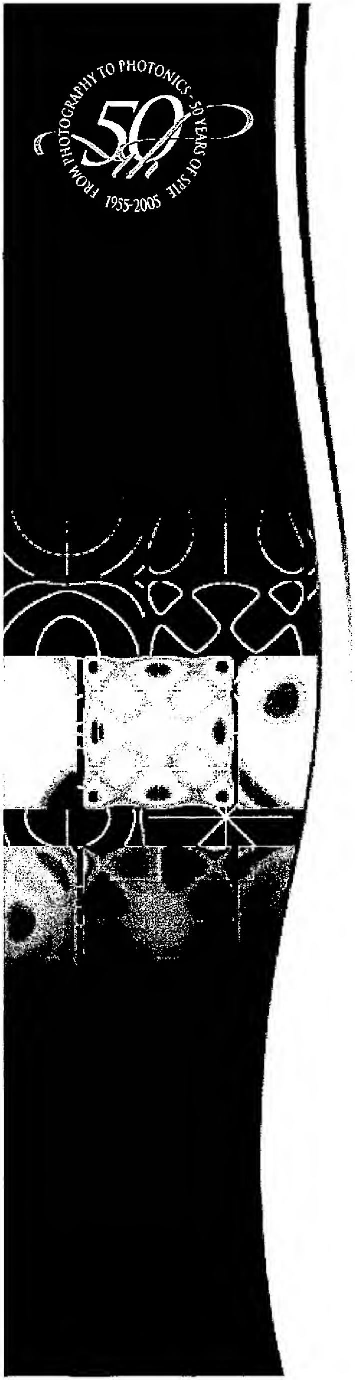

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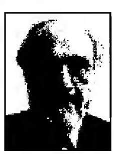

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Contents

SPIE would like to express its deepest appreciation to the symposium and conference chairs and cochairs, and programme committee members who have so generously given of their time and advice to make this symposium possible. The symposium, like our other conferences and activities, would not be possible without the dedicated contribution of our participants and members.

This Advance Programme is based on commitments received up to the time of publication and is subject to change without notice.

SPIE's Project Manager for this symposium is Karin Burger. For information about the technical programme, email: meetinginfo@spie.org.

increase the focal depth of a tracking lens. The design is based on the requirements by highly accurate tracking that the point-spread function (PSF) of the lens keep an even and concentrated energy distribution when the lens is defocused. To achieve this purpose, a multi-level phase-shifting apodizer is introduced on the pupil plane of the lens. The function of the apodizer is to control the energy distribution of the 3D diffraction pattern near the focal region and make the effective spot size uniform or minimum variation along optical axis. The pattern of the 3D PSF of the lens with the apodizer shapes closed to an extended cylinder. New method used to search and optimize the design of the phase apodizer that meet the requirements of a particle tracking system will be studied. Theoretical analysis and experiment verification will be given in support of the method.

5962-41, Session 5

Tolerance analysis of optical systems containing sampling devices

G. C. Curatu, C. E. Curatu, Univ. of Central Florida (USA)

A variety of optical systems use nowadays adaptive optics. These systems are equipped with wavefront sensors, which are often sampling devices measuring the slope of the wavefront at discrete points across the pupil (e.g. Shack-Hartmann sensors). The accuracy of the sampled output signal is always affected by the fabrication and alignment tolerances of the wavefront sensing optical system. Typically it is a requirement to express the measurement error in terms of input wavefront, so the optical output error has to be converted into wavefront measurement error. This conversion cannot be obtained directly from a conventional tolerance analysis because of the wavefront braking by the sampling device. The tolerancing method proposed in this paper solves the problem of converting conventional merit function into input wavefront measurement error. The proposed method consists of two parts. First, a Monte Carlo tolerance analysis based on a specific merit function is performed, and a 90% border system is chosen. Then, an optimization is applied to the 90% border system, by varying a dummy phase surface introduced at the entrance pupil of the system. A concrete example is presented.

5962-42, Session 5

Design of off-axis diffractive optical elements in the resonance domain of light diffraction

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Kinoform blazed diffraction grating, geometrical optics and Fourier transforms based on scalar diffraction are common tools in diffractive optics design, despite of their limited applicability for small grating periods. Alternative numerical methods of rigorous diffraction theory are more powerful and general, but are more complex and loose some physical sense. We will present a new method that combines the main advantages of scalar diffraction design with rigorous diffraction design. In this method we exploit resonance domain surface relief gratings rather that the usual thin blazed gratings, for achieving very high local diffraction efficiencies. It is mainly useful for designing diffractive optical elements with high offset angles, to which a local grating model is applicable, and where 1st diffraction order is determined by geometrical optics. Our design is based on an effective grating model, which generalizes the effective medium theory to the case of resonance domain surface relief gratings by considering both first order and zero order of diffraction. Modeling the surface relief gratings as an effective Bragg grating with two diffraction orders provides closed form analytical solutions for diffraction efficiency and phase as a functions of the gratings parameters. We show that local grooves parameters (period, depth, detour and slant angle) may be chosen with simple analytical equations so as to change the local diffracted beam direction with high diffraction efficiency. Computer simulations of specific diffraction gratings and off-axis diffractive lens confirm the validity and applicability of our method.

5962-43, Session 5

High-efficiency transmission gratings for unpolarized illumination: an intelligible analysis of the diffraction process

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Due to the fast progress in developing high-power femtosecond laser systems for micromachining and material processing applications the design and fabrication of highly efficient diffraction gratings, which are involved in most of those setups, is currently of great interest. These gratings can be metallic or dielectric reflection as well as transmission gratings, at which the last-named, e.g. made of fused silica, apparently exhibit the highest damage resistance. Numerical calculation of these fused silica transmission gratings show that a diffraction efficiency of 98% even for unpolarized illumination can be achieved if a rectangular groove profile is assumed.

However, this numerical treatment by itself does not give much insight to the mechanisms that lead to this remarkable effect. For gaining higher design potential and to give a deeper understanding of the processes which take place in the grating, a phenomenological representation of the structure has been developed on the basis of modes which propagate vertically in the direction normal to the substrate. The explicit modal analysis discloses the explanation of the highly-efficient diffraction for both polarizations by a very simple interference mechanism. This representation teaches also that no high field concentration in the ridges is expectable, therefore the damage threshold will in principle not be decreased.

5962-44, Session 5

Use of diffractive optical elements in lithographic projection lenses

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Projection lenses for high resolution lithography have large NA and work at small wave-lengths. In the wavelength regime of VUV (e.g. 193nm), there is a very limited number of optical glasses available, namely fused silica and calcium fluoride. The latter is very expen-sive and used only sparely, leading to limited possibilities to correct color.

In addition to catadioptric approaches, another way to deal with color aberrations is the use of diffractive optical elements (DOEs). They have negative dispersion coupled with positive power and they do not contribute to the Petzval sum. Moreover, it is easy to integrate an aspherical functionality into the structure of the DOE.

The largest challenge for a real world application of DOE in projection optics is the diffrac-tion of light into unwanted diffraction orders, which never can be suppressed completely.

These unwanted orders can lead to stray light and contrast loss if not properly controlled by the designer.

Usually a DOE is placed close to the aperture stop to correct axial color. That stop of a litho-graphic projection lens often is located at the largest diameter, causing some serious fabrica-tion difficulties for the DOE. For this reason a class of lenses with intermediate image is of interest. Here, the accessible image of the aperture stop enhances the possibilities to arrange the stop and the DOE. This allows a convenient trade off between fabrication challenges and aberration correcting properties. We present different lens designs that take advantage of the named properties of DOEs at high numerical aperture.

5962-45, Session 5

Combined elements for beam shaping and polarization management

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Micro and nano optics enable the control of light for producing intensity distributions with given profiles, propagation properties and polarization states. The higher the requirements on the optical function, the more complicated will be its realizing with a single element surface or a single element class. Combinations of refractive and diffractive, both diffractive or sub wavelength structures with each other give the ability to link the advantages of different element classes or different element functions for realizing the optical functionality.

In the paper we discuss different examples of combinations for DUV applications. In detail we present a diffractive - diffractive beam homogenizer with NA of 0.3 that show no zero order. A binary phase grating for polarization control combined with a beam shaping element will be presented. The polarized order of this grating shows an efficiency of about 90% with a degree of polarization better than 90%.

Wave optical and rigorous design strategies and simulations as well as the optical measurements will be discussed for the given examples.

5962-46, Session 5

Diffuser technology for illumination

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Diffuser technology is known in diffractive optics for several decades and